PHYSICS

A Textbook for Grade 10

P10TB

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Foreword

Liberia, having gone through a period of utmost turmoil till 2003, due to the civil wars, is still reeling under its effect and the added trauma of Ebola in 2014 and effects of the COVID-19 outbreak in 2020. The Liberian government, in the past decade, has made valiant efforts to bring order to the lives of its people. In one such effort, the Ministry of Education (MoE) brought changes to the National Curriculum Framework which are relevant to the present generation, and which would prepare them to meet the challenges of the changing trends of the world. The National Curriculum Framework (NCF) 2018 recommends a change in basic assumptions in the teaching learning process from behaviorist to constructivist approach — moving from hardcore print material to the digital world. Keeping in consideration the sociocultural context and varied experiences of learners as laid down in the Framework, our Teaching Learning Materials are expected to be competent to use multiple methods and techniques like e-learning resources, energized textbooks, and readily available reference material to engage the learners.

As a first initiative, the MoE, through its World Bank-funded Improving Results in Secondary Education (IRISE) project, has adapted textbooks for Grades 10 to 12 in five subjects — English Language and Literature, Mathematics, Biology, Physics and Chemistry.

The National Curriculum Framework, 2018, recommends that children's learning at school is a reflection of their life outside the school and shows them the path to become a responsible citizen who makes knowledge-based choices.This principle marks a departure from the legacy of teacher centered learning to student centered learning. The syllabi and textbooks developed on the basis of the NCF indicate a serious attempt to implement the idea of Activity Base Learning (ABL). We hope these measures will take us ahead in the direction of building a system of education as outlined in the NCF.

Combined with the efforts by the school principals and teachers this will encourage children to reflect on their own learning and to pursue imaginative activities and questions. With this in mind, perhaps for the first time in our country, we are able to provide separate subject specific textbooks accompanied with guides for teachers for 10–12 grades. Not only have these been developed, adapted and modified to the Liberian context, each of the eight Minimum Learning Competencies (MLCs) have been included in each textbook. So as to reach every high school student, for the first time in the country's history we have included the digitized form of the textbook accessible by a Quick Response (QR) code given in each book. Not only does it have the digitized textbook, but it provides additional learning materials for use by students, teachers and interested persons. The links to these e-resources and digitized material is being made available on the MoE's website.

The Textbooks and Teacher Guides have reached the hands of the students after a rigorous quality evaluation by carefully handpicked subject specialists by the MoE, to whom the Ministry expresses gratitude. For the success of this project, I acknowledge the contributions of the IRISE Project Team in the World Bank, and in particular, the Task-Team Leaders; the Project Implementation Team in Liberia headed by its Coordinator Abraham A. Kiazolu II, supported by the Executive Director of the Center of Excellence for Curriculum Development and Textbooks Research, Mrs. Julia K. Sandiman-Gbeyai and her technical working group (TWG), and the International Textbook Consultant and Advisor, Dr Shveta Uppal engaged by the MoE. These notwithstanding would not have been possible without the guidance of the Senior Management Team (SMT) of the Ministry of Education, and in particular, the Deputy Ministers for Instructions, Administration, and Planning, Research and Development, respectively.

Professor Dao Ansu Sonii, Sr.
Minister of Education
Republic of Liberia

Monrovia, Republic of Liberia
January 24, 2023

Acknowledgments

The development of textbooks contributes to the quality of teaching and learning that go on in the classroom.

The Ministry of Education (MoE) has aligned its Curriculum for Grades 10–12 to the National Curriculum Framework (NCF) of 2018. To ensure the provision of Teaching Learning Materials (TLMs) that support the revised curriculum, the Ministry has sought, reviewed and adapted a new set of textbooks and teacher guides along with digitized contents and e-learning resources for the five core subjects taught at the Senior Secondary education level, namely English Language and Literature, Mathematics, Biology, Chemistry and Physics, through an internationally competitive bidding process from the market supported by the World Bank funded Improving Results in Secondary Education (IRISE) Project.

With profound gratitude and honor, we recognize the Senior Management Team of the Ministry, headed by the Coach, Professor D. Ansu Sonii, Sr., for the strategic decision to make teaching learning materials available and accessible to all in the Liberian Senior Secondary School System, and for providing directions through the process of securing these textbooks and other teaching learning materials for our students and teachers. Our special thanks and appreciation to the World Bank for the financial support towards this policy intervention, and its education task-team including Alonso Sanchez, Oni Lusk-Stover and Binta B. Massaquoi for all their technical inputs offered throughout the process to ensure the kind of quality TLMs the Liberian students deserve are made available for improved learning outcomes.

We would like to specifically recognize the invaluable contributions of the 15 subject experts selected by the MoE from across the various education systems and the West African Examinations Council (WAEC) to evaluate, review and sign off on these teaching learning materials. They didn’t just deliver according to our expectations, but also ensured the contextual relevance of the materials to the Liberian Secondary Education Curriculum and its minimum learning competencies (MLCs). These subject experts include Professor Isaac Saye-Lakpoh Zawolo – *Superintendent* of the Monrovia Consolidated School System (MCSS), Mr. Matthew V.Z. Darblo, Sr. – *Mathematics Instructor* at the University of Liberia (UL), Mr. Charles Tieh Bropleh – *Mathematics Specialist* (MoE), Mrs. Linda Y. Dean – *English Specialist*, Mr. Hassan M. Bangura – *English Language and Literature Expert*, Mr. J. Emmanuel Milton – *English Specialist* (MoE), Mr. Moses K.M. Togbah – *Physics Specialist*, Mr. Prince A. Dossen – *Physics Specialist*, Mr. Benjamin Koryah – *Physics Instructor* at the University of Liberia (UL), Mr. Dominic Dugbe Doe – *Chemistry Specialist*, Mr. Patrick A. Anderson, Sr. – *Director o*f the Division of Technical and Vocational Education (MoE), Mr. Kandakai Massaquoi – *Chemistry Specialist*, Ms. Patricia N. Doe – *Head* of Biology Department, African Methodist Episcopal University (AMEU), Mr. Job Carpenter – *Biology Specialist* and Mr. Prince Philip K.A. Aderibigbe – *Biology Specialist*.

The MoE is sincerely grateful to Dr Shveta Uppal, the *International Textbook Consultant* engaged by the IRISE Project to provide technical guidance and quality assurance support to the revising of the Textbooks Management Guidelines (TMG) and the procurement process leading to the provision of textbooks, teacher guides, digital contents and e-learning resources for the Senior Secondary School System in Liberia in accordance with the revised TMG. Heartfelt thanks and appreciations also to the *Executive Director* for the Center of Excellence for Curriculum Development and Textbooks Research, Mrs. Julia K. Sandiman-Gbeyai, and members of her Technical Working Group (TWG) for taking up the responsibility to lead the process of making textbooks and other TLMs available to Liberian students and teachers.

Lastly, we acknowledge the IRISE Project Delivery Team led by Mr. Abraham A. Kiazolu, II – *Project Coordinator*, Mr. Fuseini A. Abu – *International Procurement Specialist* and Mr. Lawrence S. Taylor – *Project Control Specialist* who coordinated the entire process.

We remain grateful to you all!

Hon. Alexander N. Duopu, Sr.,
Deputy Minister for Instruction
Ministry of Education, Republic of Liberia
#The Teacher

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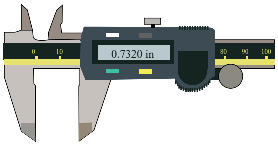

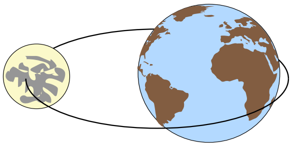

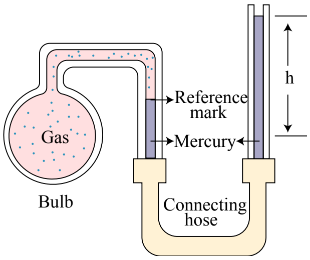
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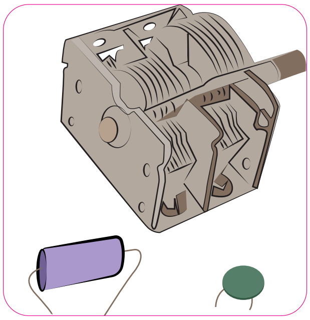

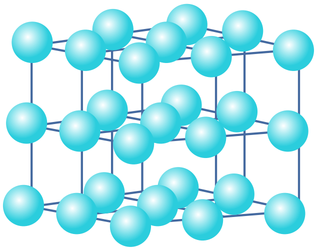

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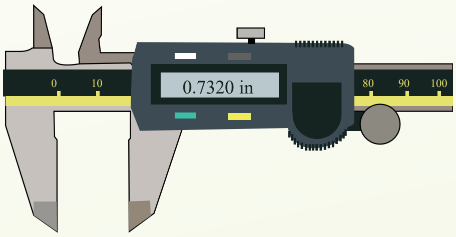
CHAPTER 1

INTRODUCTION TO PHYSICS AND PROPERTIES OF MATTER

Chapter Contents



Chapter Outcome

You will be able to:

- appreciate the importance of Physics in everyday life and the importance of making accurate measurement of physical quantities and their applications in science and technology.

Introduction

Have you ever imagined life without electricity, internet, mobile phone, television and radio? Do you know that all the above amenities are the products of Physics?

The word Physics is derived from a Greek word "Phusika", which means natural thing or nature. Therefore, Physics is about the basic things found in nature. It is about motion, forces, energy, and matter in nature. The scholars who are interested in such studies are known as **physicists**. Physics is a science that makes it possible to explain things and phenomena around us. Physics is undeniably very important in our daily lives. Physics is applicable in electricity, means of transportation, means of communication, and computers, etc.

Upon completion of this topic students will be able to:

- discuss the importance of Physics;
- identify some basic Mathematical Concepts (scientific notation, significant figures).
- distinguish between fundamental and derived physical quantities and their units.
- analyze dimensional Analysis in terms of the relationship between fundamental and derived quantities.
- measure with various measuring instruments
- distinguish between density and relative density.

A. Branches of physics

Generally, the major discoveries in physics had begun with the innovations taken up by Newton and Einstein. Based on their contribution, Physics is broadly divided into two branches: Classical Physics (Newtonian physics) and Modern Physics (Einstein's Physics).

Classical physics

Physics before 1900 is considered as Classical physics. Its main subdivisions are as follows:

Mechanics

Mechanics is the branch of physics that deals with the study of motion. It works on the concept of motion of objects with or without force concept. Mechanics can be further divided into two branches namely quantum mechanics and classical mechanics. Quantum mechanics deals with the behavior of smallest particles like neutrons, protons, and electrons, while classical mechanics is the branch that deals with laws of motion of physical objects.

Optics

Optics is related to light and it deals with the behavior, production, propagation, and properties of light along with its interactions with matter. It is the study of the behavior and the analysis of infrared light, visible light, and ultraviolet rays. It is further categorized into two areas: Physical or wave optics and Geometrical Optics. Wave Optics (Study of light as waves). deals with the nature of light and other characteristics. Geometrical Optics (Study of light as particles) aims to study light interactions with different objects like lenses, mirrors, prisms, etc.

Acoustics

Acoustic is another branch of physics that deals with the study of sound, its property, production transmission, and how it is heard and how it is absorbed. It mainly involves the mechanical waves in gases, liquids, and solids which include sound, ultrasound, and infrasound.

Thermodynamics

Thermodynamics is another branch of physics which deals with the study of heat and its relation with work and energy. It also includes studies related to the transmission of heat energy by the means of convection, conduction and radiation.

Electromagnetism

There are two aspects of electromagnetism which are “electricity” and “magnetism”. It is the phenomenon of the interaction of electric fields and magnetic fields. It explains Faraday’s laws, Coulomb’s law and studies about moving charges that produce the electric and magnetic fields.

Modern physics

Modern physics focuses on explaining events after the year 1900 and its object of study tries to explain those phenomena that occur at speeds close to the speed of light. Ii is the twentieth century physics. Albert Einstein and Max Plank are the founders of this physics. In modern physics, unlike classical physics, matter and energy are not different entities; instead, they are different forms of each other.

Relativistic physics

Relativity is the branch of physics that deals with the theorem that was formulated by Albert Einstein. The theory of relativity states that space and time are relative and all the motion that occurs in this universe are relative to a frame of reference.

Atomic physics

Atomic physics is a branch of physics that manages the creation of the particle separated from the nucleus. It is responsible for the study of the atom: its structure, electronic configuration and the mechanisms of emission and absorption of energy.

Nuclear physics

Nuclear physics is a branch of physics that deals with the structure of the nucleus and the interactions of the nuclear particles. It examines the arrangement of the particles in the nucleus, the forces that hold them together, the way in which nuclei release energy in the form of natural radioactivity or due to fusion or fission reactions.

Quantum physics

Quantum physics is the branch of physics that explains the physical phenomenon by microscopic and atomic approaches and considers the dual behavior of matter. It is theoretical physics, and it specifies the laws of motion that microscopic objects obey. When quantum mechanics is applied to macroscopic objects (for which wave-like properties are insignificant) the results are the same as those from classical mechanics.

Other branches of physics

Physics is a vast area of scientific study that consists of different concepts, principles, and methodologies. This is not the end of the list of physics branches, we have other branches of physics that uses different realities to explain how the world works. They are: Astrophysics, Geophysics, Biophysics, Photonics, Meteorology, Plasma Physics, Electronics, Chemical Physics, Engineering Physics, Solid-state Physics, Particle Physics, Condensed Matter Physics, High energy physics and others.

Exercises

1. Discuss the importance of the study of physics.
2. Discuss the branches of physics

B. Basic Mathematical Concepts

Physics can be described as a quantitative science. Quantities in physics like speed, acceleration, force, momentum and energy can be described in words and they can also be described by mathematical formulas. Many concepts in physics are mathematical quantities which can be measured, calculated and quantitatively related to other measurable quantities. Thus, physics is most certainly understood more fully when the mathematics associated with the concepts is explored and understood. Mathematics is a tool of physics.

In solving physics problems, a student need to know the mathematical relationships between quantities. This section deals with the basic mathematics that is needed in solving physics problems.

Scientific notation and unit conversions

In physics we often work with very large and very small numbers. For example, the mass of the earth is about 6 000 000 000 000 000 000 000 000 kg and the mass of an electron is 0.000000 000 000 000 000 000 000 000 000 911 kg. In this form, numbers take up much space and are difficult to use in calculations. To work with such numbers more easily, you can write them in a shortened form by expressing decimal places as powers of ten (in the form $m \times 10^n$). This method of expressing numerals is called **scientific notation**.

To write numbers in scientific notation, move the decimal point until only one digit appears to the left of the decimal point. Count the number of places you moved the decimal point and use that number as the exponent of the power of ten. Thus, the mass of the Earth can also be expressed as 6×10^{24} kg and the mass of an electron is 9.11×10^{-31} kg. Note that the exponent is positive when the decimal point is moved to the left and negative when the decimal point is moved to the right.

Key Terms

- A method of writing very big and very small numbers using the powers of ten is known as scientific notation.

Exercises

Express each of the following numbers in scientific notation with 2 significant figure:

(a) 0.054
(b) 10000
(c) 0.000000738
(d) 1230000

Trigonometry

The triangle shown below is a right triangle (that is, a triangle with two sides joined at 90°). Trigonometry is a mathematical equation that relates the sides of a right triangle with the angle between the lengths of the sides.

The sides a, b and c are related by the Pythagorean Theorem:

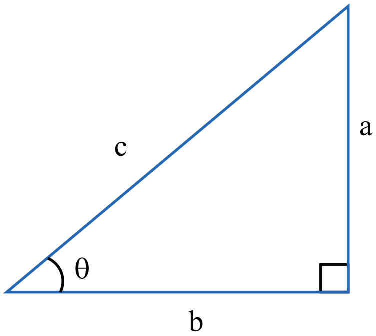
$$c^2 = a^2 + b^2 \Rightarrow c = \sqrt{a^2 + b^2}$$

For the angle θ shown in the figure: a is the opposite side, b is the adjacent side and c is the hypotenuse.

$$\sin\theta = \frac{\text{opposite}}{\text{hypotenuse}} = \frac{a}{c} \Rightarrow \theta = \sin^{-1}\left(\frac{a}{c}\right)$$

$$\cos\theta = \frac{\text{adjacent}}{\text{hypotenuse}} = \frac{b}{c} \Rightarrow \theta = \cos^{-1}\left(\frac{b}{c}\right)$$

$$\tan\theta = \frac{\text{opposite}}{\text{adjacent}} = \frac{a}{b} \Rightarrow \theta = \tan^{-1}\left(\frac{a}{b}\right)$$



The angle θ determined by using any of the above relations will give us the same value.

Examples

For the displacement vectors shown in the figure determine the magnitude and direction of the resultant using the analytical (calculation) method.

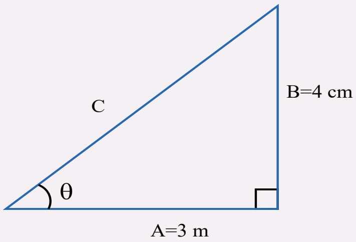
Solution: A = 3 m, B = 4 m

$$C^2 = A^2 + B^2 \Rightarrow C = \sqrt{A^2 + B^2} = \sqrt{(3m)^2 + (4m)^2} = 5\text{ m}$$

$$\sin\theta = \frac{B}{C} = \frac{4m}{5m} = 0.8 \Rightarrow \theta = \sin^{-1}(0.8) = 53^o$$

$$\cos\theta = \frac{A}{C} = \frac{3m}{5m} = 0.6 \Rightarrow \theta = \cos^{-1}(0.6) = 53^o$$

$$\tan\theta = \frac{B}{A} = \frac{4m}{3m} = 1.33 \Rightarrow \theta = \tan^{-1}(1.33) = 53^o$$



This indicates that you can use any of the trigonometric relations to determine the direction, θ, of the resultant.

C. Measurement

Physics describes the laws of nature. This description is made by measurement. To measure a physical quantity, we need some standard unit of that quantity. The comparison of any physical quantity with its standard unit is called **measurement**. Measurement is the process of obtaining the magnitude of a quantity relative to an agreed standard.

Key Terms

- **Measurement** is the comparison of any physical quantity with its standard unit.

(i) Systems of Measurement

The metric system

The metric system was introduced in France in the 1790s and is now being used officially by many countries around the world. The metric system is based on the international decimal system, which are multiples and sub-multiples of 10. It is very convenient for calculation in our decimal system. The Metric system has 3 basic units namely, meter to measure the length, kilogram to measure the mass, and seconds to measure time.

1 meter = 1,000 mm	1 meter = 10 dm	1 hectometer = 100 m
1 meter = 100 cm	1 decameter = 10 m	1 kilometer = 1,000 m

Meter:

Length is measured in meters (m). Subdivisions of the meter are the millimeter, centimeter, and the decimeter, while multiples of meters include the decameter, hectometer, and kilometer.

Kilogram:

Mass is measured in kilogram (kg). It tells us how heavy or how light an object is. We can multiply and divide the base units to measure smaller and bigger units.

Second:

Time is used to quantify the duration of the events. It also helps us to set the start time or the end time of events. The base unit for time is seconds (s). Some of the conversion units of time are:

Time
1 minute = 60 seconds
1 hour = 60 minutes

1 day = 24 hours
1 week = 7 days
1 year = 12 months
1 year = 365 days
1 minute = 60 seconds

The British Imperial System

The imperial system is a system of measurement used in the United Kingdom and other Commonwealth countries. Some of the measurements from the imperial system are listed below:

- Length is measured in feet, inches, and miles.
- Volume is measured in fluid ounces, pints, and gallons measure
- Area is measured in square feet and acres.
- Mass is measured in Pounds, ounces, and stone.

In science, imperial units have mostly been replaced with the metric system. This is because the metric system is easier to understand. It uses tens, hundreds, and thousands, which are less complicated than dealing with irregular units.

Only three countries in the world use the Imperial system of measurement: Our country Liberia, Myanmar and United States of America.

The united states customary system

The United States Customary System was based on the British Imperial System. It is used in the United States and U.S. territories. In some parts it is similar to the Imperial units. Length or distance units include the inch, foot, yard and mile.

1 foot = 12 inches

1 yard = 3 feet = 36 inches

1 mile = 1,760 yards = 5,280 feet = 63,360 inches

As you can see from the above table, the U.S. system has no simple relation to each other, and the relations lack consistency. They are therefore difficult to remember.

Systems of units

A system of units is the complete set of units, both fundamental and derived, for all kinds of physical quantities. The common systems of units which are used in mechanics are given below:

1. CGS System. In this system, the unit of length is centimeter, the unit of mass is gram and the unit of time is second.
2. FPS System. In this system, the unit of length is foot, the unit of mass is pound and the unit of time is second.
3. MKS System. In this system, the unit of length is meter, the unit of mass is kilogram and the unit of time is second.
4. SI System. In 1971 the international Bureau of weight and measures held its meeting and decided a system of units which is known as the international system of units. It is abbreviated as SI from the French name Le system International d' Units. SI units are part of the metric system. The metric system is convenient for scientific and engineering calculations because the units are categorized by factors of 10.

Exercises

1. Compare and contrast the metric system with the British Imperial System and the United States Customary System.

(ii) Fundamental Quantities and Units

Physics can be defined as the branch of science dealing with the study of properties of materials. To understand the properties of materials, measurement of physical quantities are involved. The quantities which can be measured by an instrument and by means of which we can describe the laws of physics are called physical quantities. Example: length, velocity, acceleration, force, time, pressure, mass, and density, are physical quantities.

Generally, physical quantities are classified into two types, namely: fundamental quantities and derived quantities.

Fundamental quantities, also known as base quantities, are quantities which cannot be expressed in terms of any other quantity. It is not possible to express them using other physical quantity. They are the bases for other quantities. There are seven fundamental (basic) physical quantities: length, mass, time, temperature, electric current, luminous intensity and amount of a substance.

Fundamental Quantity	S.I unit
Length	metre (m)
Mass	Kilogram (kg)
Time	seconed (s)
Temperature	kelvin (K)
Electric current	ampere (A)
Luminous intensity	candela (cd)
Amount of substance	mole (mol)
Supple mentary Quantity	**S.I unit**
Plane angle	radian (rad)
Solid angle	steradian(sr)

In addition to the seven fundamental quantities there are two supplementary quantities: plane angle and solid angle. Plane angle is measured in radian (rad) and solid angle is measured in steradian (sr).

Key Terms

- The **quantities** which can be measured by an instrument and by means of which we can describe the laws of physics are called physical quantities.

Definition

The seven fundamental units of SI system have been defined as follows.

1. **Kilogram**. 1 Kilogram is the mass of a cylindrical prototype made of platinum and iridium alloys of height 39 mm and diameter 39 mm.
2. **Meter**. 1 meter is the distance that contains 1650763.73 wavelength of orange-red light of Kr-86.
3. **Second**. 1 second is the time in which cesium atom vibrates 9,192,631,770 times in an atomic clock.
4. **Kelvin**. 1 kelvin is the (1/273.16) part of the thermodynamics temperature of the triple point of water.
5. **Candela**. 1 candela is (1/60) luminous intensity of an ideal source by an area of 1/60000 m^2 when source is at freezing point of platinum 2042K at pressure of 101325 N/m^2.)
6. **Ampere**. 1 ampere is the electric current which it maintained in two straight parallel conductor of infinite length and of negligible cross-section area placed one meter apart in vacuum will produce between them a force 2 x 10^{-7}N per meter length.
7. **Mole**. 1 mole is the amount of substance of a system which contains many elementary entities (atoms, molecules, ions, electrons etc) in 0.012 kg of carbon isotope $^{6}_{12}C$.

(iii) Derived Quantities and Units

Physical quantities which depend on one or more fundamental quantities for their measurements or which can be derived from fundamental quantities are known as **derived quantities**. For example, velocity, acceleration, force, work, and power are derived quantities. The units used to measure derived quantities are called **derived units**. It depends on fundamental units for their measurement. SI derived units are described by mathematically combining (dividing, multiplying or powering) the base units. Some of the derived quantities and their units are given in table 1.2.

Table 1 Derived quantities and their SI units

SI derived unit	Symbol	SI base unit
newton	N	kg m s^{-2}
joule	J	kg m2 s^{-2}
hertz	Hz	s^{-1}
watt	W	kg m^2 s^{-3}
volt	V	kg m^2 s^{-3} A^{-1}

SI derived unit	Symbol	SI base unit
ohm	Ω	kg m^2 s^{-3} A^{-2}
pascal	Pa	kg m^{-1} s^{-2}

Key Terms

- Physical quantities which can be derived from fundamental quantities are known as derived quantities.

Activity 1

Show how the units of the following deriven quantities are derived from the unit of base quantities.

(a) volume, (b) density and (c) force.

(iv) Metric Prefixes and Conversions

The metric system is convenient for scientific calculations because the units are categorized by multiples and submultiples of ten. Words or symbols that represent these factors of ten are called **prefixes**. They are called so because they are placed (fixed) before quantities. For example the prefixes **deka**, **hecto**, and **kilo** meaning, respectively, 10, 100, and 1000, and **deci**, **centi**, and **milli**, meaning, respectively, 1/10, 1/100, and 1/1000. Table 1.1 lists the standard SI prefixes, factor, powers of ten and symbols.

Table 2 SI Prefixes

Prefix	Symbol	Factor	Power	English Name
exa	E	1000000000000000000	10^{18}	quintillion
peta	p	1000000000000000	10^{15}	quadrillion
tera	T	1000000000000	10^{12}	trillion
giga	G	1000000000	10^{9}	billion
mega	M	1000000	10^{6}	million
kilo	k	1000	10^{3}	thousand

Prefix	Symbol	Factor	Power	English Name
hecto	h	100	10^2	hundred
deca	da	10	10^1	ten
(none)	(none)	1	10^0	one
deci	d	0.1	10^{-1}	tenth
centi	c	0.01	10^{-2}	hundredth
milli	m	0.001	10^{-3}	thousandth
micro	µ	0.000001	10^{-6}	millionth
nano	n	0.000000001	10^{-9}	billionth
pico	p	0.000000000001	10^{-12}	trillionth
femto	f	0.000000000000001	10^{-15}	quadrillionth
atto	a	0.000000000000000001	10^{-18}	quintillionth

Key Terms

- Words or symbols that represent the factors of ten are called prefixes.

Unit conversion and conversion factor

Often measurements are given in one set of units, such as feet, but are needed in different units, such as meter. A factor that is used to change between units, and therefore gives the relationship between two units is called a **conversion factor**. It is the number or formula you need to convert a measurement in one set of units to the same measurement in another set of units. A *conversion factor* uses your knowledge of the relationships between units to convert from one unit to another. For example, if you know that there are 2.54 centimeters in every inch.

$$\text{Conversion Factor} = \frac{2.54\text{cm}}{1\text{inch}} = \frac{1\text{inch}}{2.54\text{cm}}$$

Key Terms

- A conversion factor is a fraction that is equal to one used to convert a unit from one system to another.

Some common unit conversion factors are shown below. You can also use the reciprocal of these.

Mass: 1 kg = 1000 g, 1 g = 1000 mg, 1 ton = 1000 kg

Length: 1 m = 100 cm, 1 m = 1000 mm, 1 km = 1000 m

Time: 1 min = 60 s, 1 hr = 60 min, 1 day = 24 hr, 1 week = 7 days, 1 year = 365 days

Area: 1 m^2 = 10 000 cm^2, 1 m^2 = 1 000 000 mm^2, 1 m^2 = 100 dm^2,

Volume: 1 m^3 = 1000 000 cm^3, 1 d m^3 =1000 cm^3, 1 cm^3 = 1 000 mm^3

The following steps are recommended to convert one unit to the other using conversion factor.

Step One ↓

Choose an appropriate conversion factor that relates the given quantity with the quantity to be converted to.

Step Two ↓

Multiply the given value by the conversion factor (s).

Step Three ↓

Cancel out similar units from the numerator and denominator.

Step Four ↓

Multiply all the top numbers together, and divide by the product of bottom numbers. Wrire the result with unit left (the unit you want)

Note

The appropriate conversion factor is the one that cancel out the units you don't want.

Examples

Convert 5kilogram to gram.

Solution: The conversion factor is, $\frac{1000\ g}{1\ kg}$.

$$5\ kg = 5\ kg \times \frac{1000\ g}{1\ kg} = 5000\ g$$

Examples

How many minutes are there in 3.5 hours?

Solution: The appropriate conversion factor is $\frac{60\ min}{1\ hr}$

$$3.5\ hr = 3.5\ hr \times \frac{60\ min}{1 hr} = 210\ min$$

Exercises

1. Convert 8.0m to centimeter
2. How many seconds are there in one day?
3. Convert 72 kilometer per hour to meter per second.
4. Convert 0.5 m^2 to cm^2
5. Convert 2500 cm^3 to m^3

(v) Significant Figures

The number of figures required to specify a certain measurement are called **significant figure**. The last figure of a measurement is always doubtful, but is included in the number of significant figure. All accurately known digits in a measurement plus the first uncertain digit together form significant figures. For example, when we measure the length of a straight line using a meter rule and it lies between 7.4 cm and 7.5 cm, we may estimate it as $l = 7.43$ cm. This expression has three significant figures out of these 7 and 4 are precisely known but the last digit 3 is only approximately known.

Key Terms

- The number of figures required to specify a certain measurement are called significant figure.

Rules for counting significant figures

Rule 1. All non-zero digits are significant. For example, 2567 m has four significant figures.

Rule 2. The zeros appearing between two non-zero digits are significant, no matter where the decimal point is, if any. For example, 6.028 has 4 significant figures.

Rule 3. If the number is less than 1, the zero(s) on the right of decimal point but to the left of first non-zero digit are not significant. For example, 0.0042 has two significant digits.

Rule 4. In a number with decimal, zeros to the right of last non-zero digit are significant. For example, 4.600 & 0.002300 have four significant figures each

Rule 5. If a measurement contains no decimal point, the number of final zeros are ambiguous. These zeros may or may not be significant. For example 1300 could have two, three, or four significant figures. To avoid this ambiguity, write such numbers in scientific notation. When 1300 is written as 1.3×10^3 it will have two significant figures. When written as 1.30×10^3 it will have three significant figures, and when written as 1.300×10^3 it will have four significant figures.

Rule 6. The power of 10 is irrelevant to the determination of significant figures. For example, in the measurements 2.30 m $= 2.30 \times 10^2$ cm $= 2.30 \times 10^3$ mm $= 2.30 \times 10^3$ km. The significant figures are three in each measurement.

Note

The number of significant figures do not change if we measure a physical quantity in different units. For example, 14.5 cm = 145 mm = 0.145 m = 14.5×10^{-2} m. All have three significant figures.

Exercises

Determine the number of significant figures in the following measurements:

(a) 0.0009
(b) 15,450.0
(c) 6×103
(d) 87.990
(e) 30.42

Significant Figures in Algebraic Operations

In Addition or Subtraction

When adding or subtracting measured quantities, the final result should have the same number of decimal places as there are in the quantity with the fewest **decimal places**. That is, in calculations where measured quantities are added or subtracted, the final answer can have only one "uncertain" figure, so it stops at the place on the right where any of the data first stops.

Examples

If l_1= 4.326 m and l_2 = 1.50 m Then, $l_1 + l_2$ = (4.326 + 1.50) m = 5.826 m

As l_2 has measured up to two decimal places, therefore $l_1 + l_2$ = 5.83 m

In multiplication or division:

In a multiplication or division of two or more quantities, the number of significant digits in the answer is equal to the number of **significant digits** in the quantity which has the minimum number of significant digit.

Examples

If the height of a rectangle is h = 12.5 m and its breadth is b = 4.125 m. Then, area (A) = b × h = 12.5 × 4.125 = 51.5625 m^2.

As b has only 3 significant figures, therefore A= 51.6 m^2

Examples

Find the speed of a car that travels 11.21 meters in 1.3 seconds.

$$v = \frac{s}{t} = \frac{11.21}{1.3} = 8.623076923$$

The answer contains 10 significant figures. However, since the value for time (1.3 s) is only 2 s.f. we write the answer as 8.6 m s^{-1}.

The number of significant figures in any answer should reflect the number of significant figures in the given data.

Exercises

1. Use the rules for significant figures to find the answer to the addition problem 21.4 + 15 + 17.17 + 4.003.
2. A water tank has a mass of 3.64 kg when it is empty and a mass of 51.8 kg when it is filled to a certain level. What is the mass of the water in the tank to the correct number of significant figures?
3. A rectangular plot of land measures 32.30 m by 210 m. Find the area, taking into account the correct number of significant figures.
4. The density of an object is equal to its mass divided by its volume. What is the density of an unknown material of mass 1.80 kg and volume 6.0×10^{-4} m^3?

Rules of rounding off significant figures

1. If the digit to be dropped is less than 5, then the preceding digit is left unchanged. Example, 1.54 is rounded off to 1.5.
2. If the digit to be dropped is greater than 5, then the preceding digit is raised by one. Example, 2.49 is rounded off to 2.5.
3. If the digit to be dropped is 5 followed by digit other than zero, then the preceding digit is raised by one. Example, 3.55 is rounded off to 3.6.
4. If the digit to be dropped is 5 or 5 followed by zeros, then the preceding digit is raised by one, if it is odd and left unchanged if it is even. Example, 3.750 is rounded off to 3.8 and 4.650 is rounded off to 4.6.

Exercises

Round off the following numbers to three significant digits

(a) 15462 (c) 14.750

(b) 14.745 (d) 14.650×10^{12}

(vi) Accuracy and Precision

Accuracy is how close a measurement is to the true or accepted value. An accurate measurement yields a result that is very close to the true or accepted value. For example, you are measuring the value of acceleration due to gravity in your school experimentally. The accepted value of acceleration due to gravity on the surface of Earth is known to be 9.8 m/s^2. You may obtain the following three measurements: 9.9 m/s^2, 9.7 m/s^2, and 10.0 m/s^2. These measurements are quite accurate because they are very close to the correct value of 9.8 m/s^2. In contrast, if you had obtained a measurement of 12.0 m/s^2, your measurement would not be very accurate.

Precision is the degree of consistency and agreement among independent measurements of the same quantity. Measurements are said to be precise if they yield very similar results when repeated in the same manner. Precision is sometimes referred to as repeatability or reproducibility. A measurement which is highly reproducible tends to give values which are very close to each other. One way to analyze the precision of the measurements would be to determine the range, or difference, between the lowest and the highest measured values.

In the above experiment of determining the acceleration due to gravity, the lowest value was 9.7 m/s^2 and the highest value was 10.0 m/s^2. Thus, the measured values deviated from each other at most by 0.3 m/s^2. These measurements were relatively precise because they did not vary too much in value. However, if the measured values had been 9.7 m/s^2, 11.0 m/s^2, and 12.9 m/s^2, then the measurements would not be very precise because there would be significant variation from one measurement to another.

The concepts of precision and accuracy can also be demonstrated by the series of targets below. If the center of the target is the "true value", then A is neither precise nor accurate. Target B is precise (reproducible) but not accurate. The average of target C's marks give an accurate result but precision is poor. Target D demonstrates both precision and accuracy.

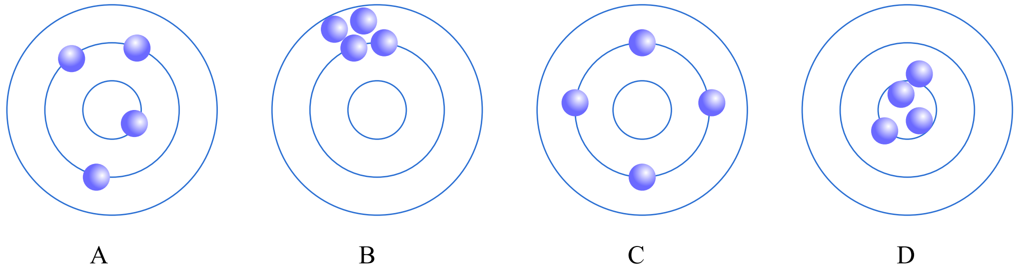


Figure 1. Accuracy and precision

Key Terms

- Accuracy is how close a measurement is to the true or accepted value.
- Precision is the degree of consistency and agreement among independent measurements of the same quantity.
- Uncertainty is a quantitative measure of how much your measured values deviate from a standard or expected value.

Accuracy, precision, and uncertainty

Every measurement has some **uncertainty**, which depends on the device used and the user's ability. The total range of values with in which the measurement is likely to lie is known as its **uncertainty**. For example, a measurement of 46.0 ± 0.5cm implies that the most likely value is 46.0cm, but could be as low as 45.5cm or as high as 46.5cm. The uncertainty in the measurement is ± 0.5cm.

The degree of accuracy and precision of a measuring system are related to the uncertainty in the measurements. If your measurements are not very accurate or precise, then the uncertainty of your values will be very high.

Reporting uncertainty

The most common way of reporting our measurements is to show the range of values (uncertainty) that we believe includes the true value is:

Measurement = (best estimate ± uncertainty) units

$$\text{measurement} = x_{best} \pm \sigma_x$$

x_{best} = best estimate of measurement

σ_x = uncertainty (error) in measurement

The instrument you are using for measurement affects the uncertainty. The following general rules of thumb are often used to determine the uncertainty in a single measurement when using a scale or digital measuring device.

1. Uncertainty in a scale measuring device is equal to the smallest increment divided by 2.

   $$\sigma_x = \frac{\text{smallest increment}}{2}$$

2. Uncertainty in a digital measuring device is equal to the smallest increment.

   $$\sigma_x = \text{smallest increment}$$

Examples

1. Meter stick (scale device)

   $$\sigma_x = \frac{1\text{ mm}}{2} = 0.5\text{ mm} = 0.05\text{ cm}$$

2. Digital Balance (digital device)

   If a digital balance reads the mass of an object to be 5.7513 kg, its uncertainty is

   $$\sigma_x = 0.0001\text{ kg}$$

Note

that the uncertainty have the same decimal place as the measurement.

Types of uncertainties

There are three types of uncertainty: absolute, fractional and percentage uncertainties.

Absolute uncertainty is the actual uncertainty in a reading taken using a specific piece of apparatus.

Fractional uncertainties

To calculate the fractional uncertainty of a piece of data we simply divide the uncertainty by the value of the data.

Percentage uncertainties

To calculate the percentage uncertainty of a piece of data we simply multiply the fractional uncertainty by 100%.

Examples

If a measurement of time is given to be 1.2 s ± 0.1

Absolute uncertainty = ± 0.1

Fractional uncertainties = $\frac{0.1}{1.2} = 0.08$

Percentage uncertainty: = $\frac{0.1}{1.2} \times 100\% = 0.08 \times 100\% = 8\%$

Uncertainties in calculations

Addition and subtraction

When performing additions and subtractions we simply need to add together the absolute uncertainties.

Examples

Add the values 1.2 ± 0.1, 12.01 ± 0.01, and 7.21 ± 0.01

Best estimate = 1.2 + 12.01 + 7.21 = 20.42

Uncertainty = 0.1 + 0.01 + 0.01 = 0.12

Result = 20.42 ± 0.12

Multiplication and division

When performing multiplications and divisions, we simply add together the percentage uncertainties.

Examples

Multiply the values 1.2 ± 0.1 with 12.01 ± 0.01

Best estimate = 1.2 × 12.01 = 14

% uncertainty of the first measurement = 0.1 ÷ 1.2 × 100% = 8.33 %

% uncertainty of the second measurement 0.01 ÷ 12.01 × 100% = 0.083%

Total % uncertainty = 8.33 + 0.083 = 8.413 %

Result = 14 ± 8.413 %

Result = 14 ± 8.413 % (14) = 14 ± 1.17782 = 14 ± 1

Exercises

Calculate the area of a field if its length is 12 ± 1 m and width is 7 ± 0.2 m.

(vii) Errors in measurement

Errors are not mistakes. Mistakes can result from measuring a width when the length should have been measured, or misreading the scale on an instrument, or forgetting to divide the diameter by 2 before calculating the area of a circle with the formula $A = \pi r^2$.

Measurement error, on the other hand, is the difference between a measured value and the true value for that measurement. It is the amount of inaccuracy or the lack in accuracy in the measurement due to the limit of accuracy of the instrument or due to any other cause. Errors can be classified into two: Systematic errors and random errors.

KEY TERMS

- **Measurement** error is the difference between a measured value and the true value for that measurement.

Systematic errors

Systematic errors are errors that are consistently in the same direction, they are one-sided errors. A systematic error is a type of error that shows a bias or a trend. It makes your readings too high every time, or too low every time. Systematic errors are often due to a problem that persists throughout the entire mwasurement. The common sources of systematic errors are:

- faulty calibration of measuring instruments,
- poorly maintained instruments, or
- faulty reading of instruments by the user.

Examples of systematic error:

(i) Zero error

(ii) Parallax error: when seen only in one direction.

Systematic errors can be reduced by: recalibrate the instrument, improve instrument resolution, apply correction for identified error, improve procedures, shift to other methods, and change the operators. Note that, the accuracy of measurements subject to systematic errors cannot be improved by repeating those measurements.

Random errors

Random errors are errors that cause your measurements to be sometimes above the accepted value and sometimes below the accepted value. They have no pattern or bias and hence cause measurement to vary in an unpredictable manner.

Common sources of random errors are problems estimating a quantity that lies between the graduations (the lines) on an instrument, the inability to read an instrument because the reading fluctuates during the measurement, and the experimenter's inability to take the same measurement in exactly the same way.

The causes of random errors are not known. Hence, it is not possible to remove them completely. Random errors can be minimized by repeating the observation a large number of times and take the average.

Key Terms

- Systematic errors are errors that are consistently in the same direction, they are one-sided errors.
- Random errors are errors that cause your measurements to be sometimes above the accepted value and sometimes below the accepted value.

Examples of random error

1. Parallax error: when seen in different angle at different time. The term ``parallax'' refer to the apparent jump of the position of a foreground object relative to distant objects when we look from two different points.
2. Air fluctuations occurring as student's open and close lab doors cause changes in pressure and temperature readings.

Experimental error is measured by its accuracy and precision. Random errors affect the precision of a measurement while systematic errors affect the accuracy of a measurement.

D. Pressure

(i) Pressure in solids

Pressure is defined as the amount of force exerted (thrust) on a surface per unit area. It can also be defined as the ratio of the force to the area (over which the force is acting). Therefore, pressure can be represented by the equation:

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

$$P = \frac{F}{A}$$

Note that pressure is directly proportional to force and inversely proportional to area. Thus, pressure can be increased either by increasing the amount of force or by decreasing the area over which it is applied. The pressure of a solid arises due to the weight of the solid.

The units of pressure are derived from the units used to measure force and area. Force is measured in newton (N) and area is measured in square meters (m^2). Therefore, pressure is expressed in N/m^2, which is called the **Pascal (Pa)**, after the French mathematician Blaise Pascal (1623–1662). Other units include the atmosphere (atm). Pressure is a scalar quantity. Pressure may also be expressed in the kilopascal (kPa), which equals 1000 Pascal.

Since pressure has only a magnitude, no direction, it is a scalar quantity.

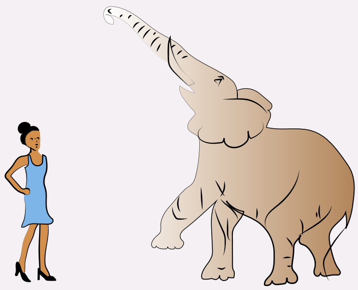
Examples

An elephant weighing 40,000 N has one foot of area 1000 cm^2 (0.1 m^2). A girl weighing 400 N has one heel of area 1cm^2 (0.0001 m^2). Compare the pressure exerted on the ground by the elephant and that of the girl.

Solution:

For the elephant: $P = \frac{F}{A} = \frac{40000\ N}{4 \times 0.1\ m^2} = 100000\ Pa$

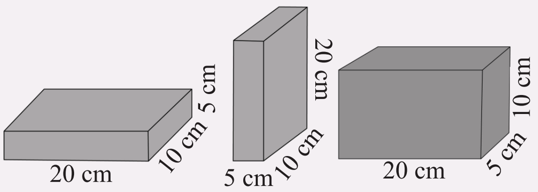
For the girl: $P = \frac{F}{A} = \frac{400\ N}{2 \times 0.0001\ m^2} = 2000000\ Pa$



So the elephant exerts a larger force (because it is heavier) but the girl's heel exerts 20 times larger pressure (because of its smaller area). Her heel would sink farther into the ground.

Examples

A rectangular metal block of weight 4 kgf and dimensions 20 cm × 10 cm × 5 cm placed in three different positions on the ground. Find the pressure exerted by the block in each case.



Find the positions where the pressure exerted on the ground is maximum (P_{max}) and minimum (P_{min})? Also, find the ratio of maximum to minimum pressure.

Solution:

Pressure exerted by the block in 1st case

$$\text{Pressure} = \frac{\text{force}}{\text{area}}$$

Pressure exerted by the block in 1st case

$$P_1 = \frac{4 \text{ kgf}}{20 \text{ cm} \times 10 \text{cm}}$$

$$= 0.02 \text{ kgf/cm}^2$$

In 2nd case $P_2 = \frac{4 \text{ kgf}}{5 \text{cm} \times 10 \text{cm}}$

$$P_2 = 0.08 \text{ kgf/cm}^2$$

In 3rd Case

$$P_3 = \frac{4 \text{ kgf}}{20 \text{ cm} \times 5 \text{ cm}}$$

$$= 0.04 \text{ kgf/cm}^2$$

In 2nd case pressure is maximum and in 1st case pressure is minimum, therefore

$$\frac{P_{max}}{P_{min}} = \frac{P_2}{P_1}$$

$$= \frac{(0.08 \text{ kgf/cm}^2)}{(0.02 \text{ kgf/cm}^2)}$$

$$= 4$$

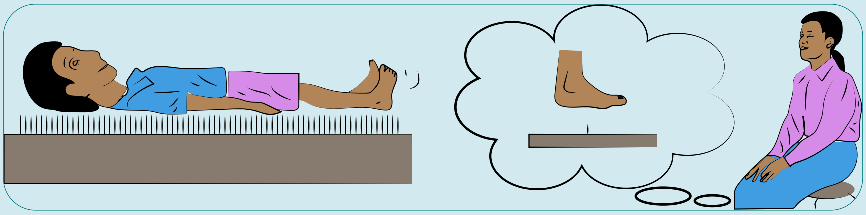
$$\frac{P_{max}}{P_{min}} = 4$$

ACTIVITY 2

Discuss in group and explain the reason for the following events.

(a) It is dangerous to stand on a nail, but there is no danger in sitting or sleeping on a board with nails as shown in the figure.

(b) Knifes need to be sharp in order to cut things easily.



Safety precaution:

Do not try this alone, unless you are with your teacher or any senior family member.

Exercises

1. Define pressure and state its SI unit.
2. A block of mass 5.0 kg with sides 10 cm by 20 cm by 30 cm is placed on a horizontal surface. Calculate the maximum and minimum pressure exerted by the block on the surface on which it is placed.
3. A man whose mass is 90 kg stands on a floor. If the area of contact between his feet and the floor is 45 cm^2, determine how much pressure he able to exert on the floor.

(ii) Pressure in Liquids

Density and relative density

Density is the ratio of the mass to the volume of a body. Relative density, on the other hand, is the ratio of the density of an object and the density of some other reference object (usually water) at some given temperature. Density is measured in kg/m^3. Density is unique for each body, while the same body can have numerous relative densities (compared to different reference bodies). The density (ρ) of an object can be defined mathematically as the mass (m) divided by the volume (V):

$$\rho = \frac{m}{V}$$

The relative density (RD) or specific gravity (SG) of a substance is the ratio of density of a substance to the density of water at 4°C. Since the units for both the numerator and denominator are same, they cancel each other. Thus relative density has no units.

$$RD = \frac{\text{density of substance}}{\text{density of water}}$$

Key Terms

- Pressure is defined as the amount of force exerted on a surface per unit area.
- The density (ρ) of a substance can be defined mathematically as the mass divided by the volume.
- The relative density (RD) of a substance is the ratio of density of a substance to the density of water at 4 °C.

Examples

A certain rock has a volume of $15 cm^3$ and a mass of 45 g. What is its density and relative density?

Solution: $\text{Density } (\rho) = \frac{\text{mass}}{\text{volume}} = \frac{45\text{ g}}{15\text{ cm}^3} = 3\text{ g / cm}^3$

$$RD = \frac{\text{density of rock}}{\text{density of water}}$$

$$RD = \frac{3\text{ g / cm}^3}{1\text{ g / cm}^3}$$

$$RD = 3$$

Exercises

1. The density of Alcohol is 800 kg/m^3. What is its relative density?
2. The relative density of mercury is 13.6. What is the density of mercury in (a) Kg/m^3, and (b) g/cm^3.
3. The density of granite is 2.8 g/cm^3, and the density of water is 1.0 g/cm^3. What is the specific gravity of granite?

Liquid pressure

The pressure of a static (non-flowing) liquid is due to the weight of the liquid column above the point of the pressure we measure. So, at any given depth, the pressure is equal to the weight of the liquid above it divided by its area. An expression for the pressure at a depth h in a liquid of density ρ can be found by considering a horizontal area A (see the figure below).

The force acting vertically downwards equals the weight of a liquid column of height (h).

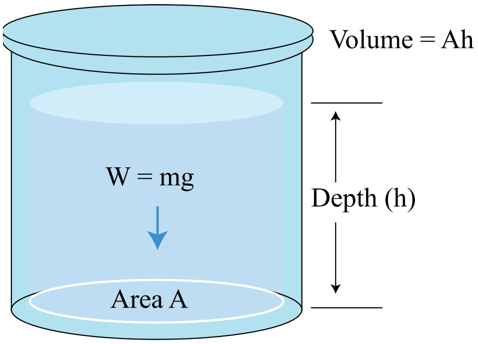


Figure 2. Pressure due to a liquid column

Height or depth of the liquid = h

Cross-sectional area = A

Volume = base area × height = Ah

Mass = density × volume = ρAh (ρ = density)

Force produced by the column = Weight of the fluid = mg = ρAhg

$$\text{Pressure} = \frac{F}{A} = \frac{\rho g h A}{A} = \rho g h$$

The above equation tells us that the pressure exerted by a liquid at rest depends only upon the depth of the fluid, the density of the fluid, and the acceleration of gravity. It is independent of shape, area or volume of the liquid. Hence, the shape of the container does NOT matter in the computation of the water pressure.

The equation (p = ρ g h) is due to the liquid column only. But if the surface of the liquid is exposed to the atmosphere, it will exert a pressure on the liquid which can't be neglected.

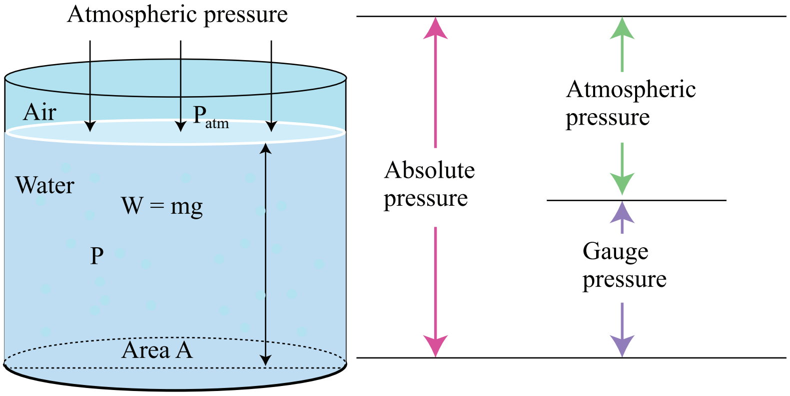


Figure 3. Absolute P = Atmospheric P + Gauge P

The total pressure, or absolute pressure, is thus the sum of gauge pressure and atmospheric pressure:

$$P_{total} = P_{atm} + \rho hg$$

where P_{total} is absolute pressure, ρhg is gauge pressure, and P_{atm} is atmospheric pressure. Absolute pressure is the sum of gauge pressure and atmospheric pressure.

$$P_{total} = P_{atm} + P_{gauge}$$

Key Terms

- The pressure of a static (non-flowing) liquid is: $Pressure = \rho gh$
- Absolute pressure, is the sum of gauge pressure and atmospheric pressure: $P_{total} = P_{atm} + \rho hg$

Depth and pressure in liquids

Pressure increases as you move away from a liquid's surface. This is seen in the experiment shown in the diagram below. Three identically-sized holes are drilled in a bucket. The pressure is greater at the bottom of the bucket so the water leaves with greater force.

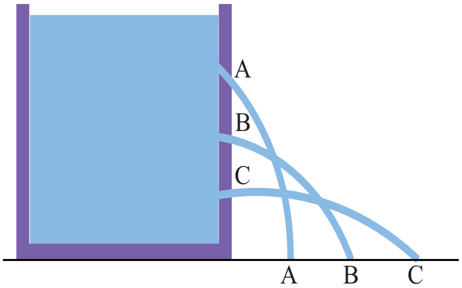


Figure 4. Variation of pressure with depth

Examples

A diver is located 20 m below the surface of a lake ($\rho = 1000\ kg/m^3$). What is the pressure due to the water?

Solution:

$$P = \rho gh = (1000\ kg/m^3)(0.2\ m)(10\ m/s^2) = 2,000\ Pa$$

Examples

A container open to the atmosphere contains water to a height of 20 cm. Find the Absolute pressure exerted by water on the base of the container. (Atmospheric pressure = 100kPa, $g = 10 m/s^2$, density of water = $1000 kg/m^3$)

Solution:

Thus: Pressure at depth h = Atmospheric pressure + ρhg

$= 100,000\ Pa + (1000\ kg/m^3)\ (0.2\ m)\ (10\ m/s^2)$

$= 102,000\ Pa = 102\ kPa$

Exercises

What difference in blood pressure will a 175 cm tall person has between his head and feet (density of blood = 1.06×10^3 kg m^{-3}, g = 10 m/s^2)?

Historiacal Note:

Blaise, Pascal (1623-1662)

Blaise Pascal was a well-known French philosopher, mathematician and physicist. He was also a Christian philosopher, inventor, and writer. Blaise, went to no school, but was taught by his father.

In 1642, at the age of 19, Pascal invented a mechanical calculator that could perform additions and subtractions. He had developed the calculator with the aim of helping his father to calculate the taxes more quickly and accurately. Pascal's machine was called the Pascaline. The machine was also capable to do multiply and divide by repetition."

During the same time period (1640), he invented the syringe and created the hydraulic press. Ahydraulic press is an instrument based upon the principle that became known as Pascal's law.

In mathematics, his most significant contribution was the development of probability theory.

In the 1970s, the Pascal (Pa) the SI unit of pressure, was named after Blaise Pascal in the honor of his contributions to science. The programming language, Pascal, is also named after him.

Activity 3

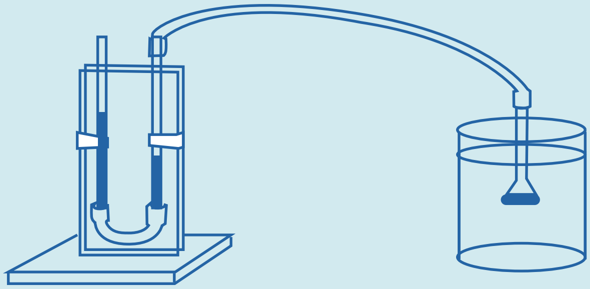
Objective of the activity: To show that liquids exert pressure

Materials required: Two 15cm long glass tubes or transparent straws (pen cover can be used), rubber tube, can, water, colored water, piece of rubber (plastic sheet) and funnel

Procedure:

- Connect two 15 cm lengths of glass tubing with a short length of rubber tubing
- attach them to an upright as shown in the diagram.
- Put some coloured water in the tubes to a depth of about 6 or 8 cm. This is your pressure gauge or manometer .

- Cover a small funnel with thin rubber stretched tightly and tie it securely with thread or string.
- Attach the funnel to the manometer with a 30 cm length of rubber tubing.
- Push the funnel into a pail of water and watch the manometer.

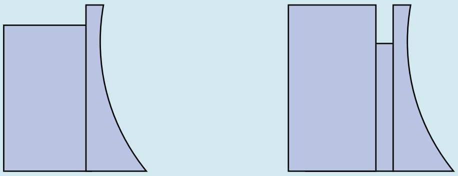


Questions

1. Introduce the funnel into the liquid in the can. Explain what you observe.
2. Gradually lower it to greater depths. Explain what you observe.
3. Keeping the funnel fixed at a certain depth turn it in different directions. Explain what you observe.
4. Displace the funnel to different points at the same horizontal level. Explain what you observe.
5. Write the conclusion of your observation

Activity 4

In constructing a dam its thickness should increase as you go down like the one shown in figure. What is the reason?



(a) (b)

Applications of liquid pressure

(i) Hydraulic machines

We know that liquids are almost incompressible (i.e. their volume cannot be reduced by squeezing). As a result they 'pass on' any pressure applied to them. Hydraulic machines work by use of these facts. Their function is based on Pascal's Principle stated below!

> "A change in pressure applied to an enclosed fluid is transmitted unchanged to every point within the fluid"

An important application of Pascal's principle is the hydraulic press. Here we see two cylinders, a smaller one of cross-sectional area A_1, and a larger one of cross-sectional area A_2. The cylinders, each of which is fitted with a piston, are connected by a tube and filled with an incompressible fluid. Now, suppose we push down on piston 1 with the force F_1. The pressure in that cylinder increases by the amount, $\Delta p = \frac{F_1}{A_1}$. By Pascal's principle, the pressure in cylinder 2 increases by the same amount. Thus, $\Delta p = \frac{F_2}{A_2}$. Equating these two equations, and rearranging for F_2 gives

$$\frac{F_1}{A_1} = \frac{F_2}{A_2} \Rightarrow F_2 = \left(\frac{A_2}{A_1}\right) F_1$$

Therefore, F_2 is larger than F_1 by the factor A_2/A_1. That is why a large load, such as a car, on the large piston can be moved by a much smaller force applied on the smaller piston. Hydraulic brakes, hydraulic jacks, car lifts, forklifts, and other machines make use of this principle. Figure1.5 shows the principle on which they work.

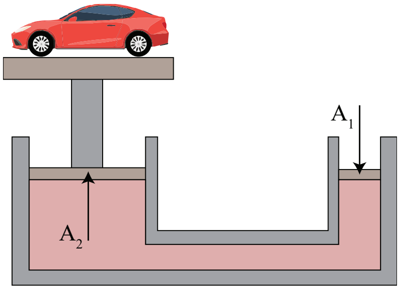


Figure 5. A Hydraulic Lift

Hydraulic fork-lift trucks and similar machines such as loaders (Figure1.6) work in the same way.

Figure 6. A hydraulic machine in action

Exercises

The smaller and larger pistons of a hydraulic press have diameters of 4 cm and 12 cm. What input force is required to lift a 4000 N weight with the output piston?

Hydraulic car brakes. In the break system of a vehicle, when the driver applies a force on the break-pedal, it is transmitted to the piston in the master cylinder. This force exerts a pressure on the oil inside the cylinder. This pressure is then transmitted through the oil to the slave cylinder near the wheel. Then the brake-pads connected to the slave cylinder are pressed to apply a pressure on the break-discs or break-drums. Since the cross-sectional area of the slave cylinder is larger than that of the master cylinder, the force applied on the break-pads by the slave cylinder is greater than the force applied by the driver on the break-pedal. This causes the wheel and hence the car to stop.

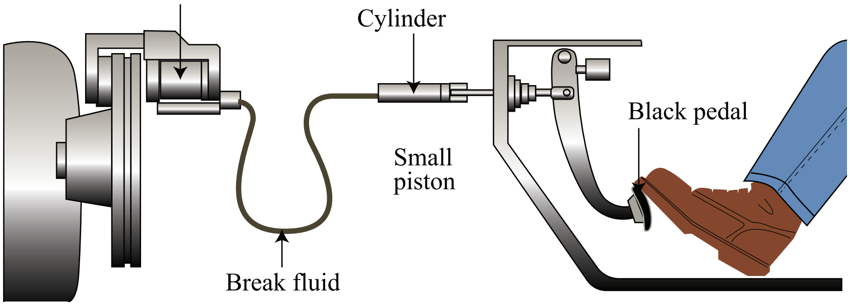


Figure 7. Hydraulic car break

Exercises

Why do deep sea divers wear special suits?

(ii) Pressure in Gases

Like liquids, gases also exert pressure on the wall of the container in which they are enclosed. Under normal conditions, there are a large number of air molecules moving at high velocities. These large number of air molecules makes frequent collisions with the walls of the container. In this interaction a force is exerted on the walls of the container and Pressure is created due to this force. In gases, we define pressure as the force exerted by the collisions of particles.

Atmospheric pressure

Air surrounds the Earth from all sides. This layer of air is called **atmosphere**. The weight of the Earth's atmosphere pushing down on each unit area of Earth's surface constitutes the **atmospheric pressure**. Most of the atmosphere's molecules are held close to the earth's surface by the force of gravity. At higher elevations, there are fewer air molecules above a given surface than a similar surface at lower levels. Hence the Earth's atmospheric pressure decreases with height from the sea level as shown in the figure. For example, the pressure at 12 km is 1000 pa but the pressure at 50 km is only 100 pa. What this implies is that atmospheric pressure decreases with increasing height.

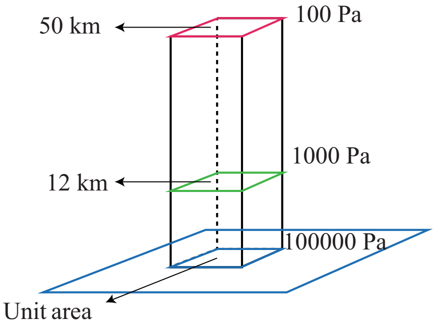


Figure 8. Variation of atmospheric pressure with altituude

Activity 5

The presence of atmospheric pressure can be demonstrated by the crushing can experiment shown in the figure below.

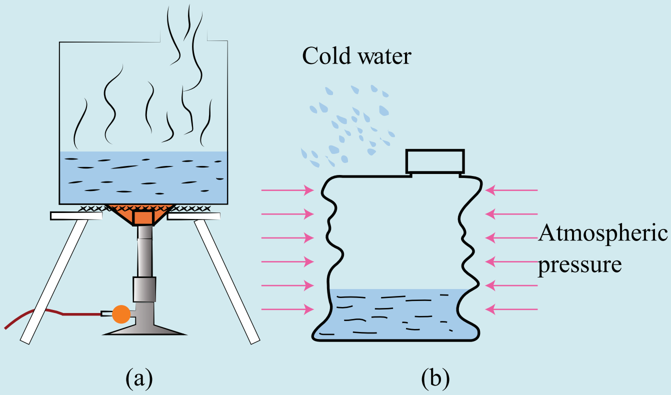


Figure 9. The crashing can experiment

The can is filled with water then heated for several minutes. After sometime, the can is sealed and then cooled by pouring cold water over it. When the water is heated, steam is produced which displaces air in the can. When cold water flows over it, steam condenses leaving a vacuum in the can. Pressure inside is thus reduced below the external atmospheric pressure. Hence the can crushes inwards.

Key Terms

- The pressure due to the sea of air which surrounds us is called atmospheric pressure. Atmospheric pressure decreases with increasing height.

Measurement of atmospheric pressure

Atmospheric pressure is measured using an instrument called a **barometer**. The following steps show how a barometer works.

Step 1: A thick glass tube (at least 1 m long) is filled with mercury completely.

Step 2: The open end of the tube is covered with a finger, inverted and then inserted in a trough of mercury.

Step 3: Atmospheric pressure acts on the surface of this trough of mercury to push the mercury into the tube. The space at the top of the barometer tube is a vacuum and exerts no pressure on the mercury column.

Step 4: The column of mercury has a pressure equal to the atmospheric pressure.

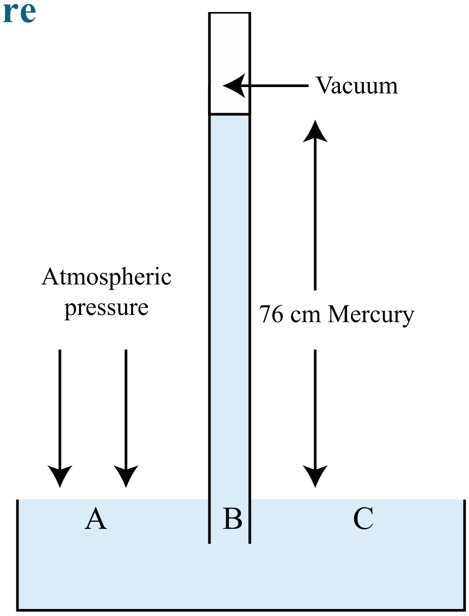


Figure 10. Barometer

Atmospheric pressure can support a liquid column in a tube. At sea level atmospheric pressure can support approximately 76 cm column of mercury equivalent to approximately 10m column of water. Mercury is thus preferred as a barometric fluid since it gives a shorter and measurable column compared to water. The value of atmospheric pressure at sea level is called the **standard atmospheric pressure** and is at times referred to as one atmosphere.

$$1 \text{ Atmospheric pressure} = \rho hg = 13600 \text{ kg/m}^3 \times 0.76 \text{ m} \times 9.8 \text{ N/kg}$$
$$= 101{,}292.8 \text{ N/m}^2 = 101 \times 10^3 \text{ Pa} = 101 \text{ kPa}$$

Key Terms

- Atmospheric pressure is measured using an instrument called a barometer.
- A manometer measures the pressure acting on a column of fluid. It is made from a U-shaped tube open on both ends.

Manometer

A manometer measures the pressure acting on a column of fluid. It is made from a U-shaped tube open on both ends. When no gas supply connected to either arms (Figure 11 (a)), Only atmospheric pressure acts on both surfaces of liquid. Thus, liquid settles at common level at A and B as pressure exerting at A and B is the same.

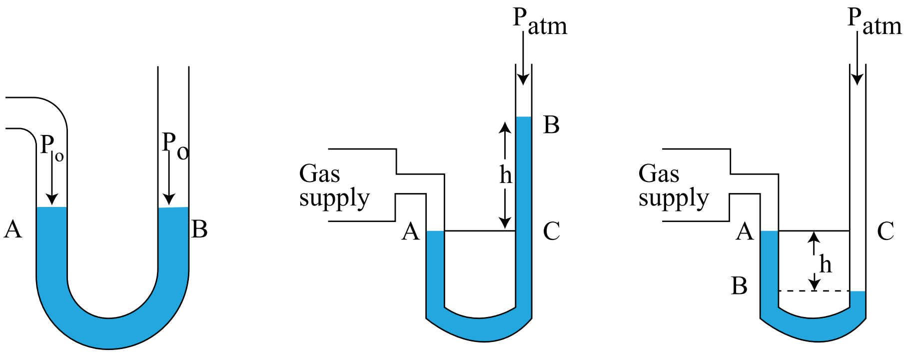


Figure 11. Manometer

When one end is connected to a source of gas whose pressure is to be determined, the other arm is open to the atmosphere. This creates a pressure difference which displaces the manometer liquid. If the source of gas has a higher pressure, the mercury in the open tube will be forced up by the gas in the other arm of the U-shaped tube (Figure 11 (b)).

The points A and C are at the same level and as such experience the same amount of pressure. The pressure at A is the gas pressure while that at C equals the pressure due to the liquid column plus atmospheric pressure.

i.e $P_A = P_C$

Gas pressure = P_{atm} + pressure due to liquid column BC

$= P_{atm} + \rho hg$

If the gas in the bulb has a pressure less than that of the atmosphere, then the height of the mercury will be greater in the arm attached to the source. In this case, the pressure of the gas in the bulb is the atmospheric pressure minus the pressure in the column.

i.e $P_A = P_C$

$= P_{atm}$ − pressure due to liquid column AB

$= P_{atm} - \rho hg$

Activity 6

Collect tubes of different heights and sizes. Fill them completely with mercury, cover its open end with your finger and immerse them in a trough of mercury. When you release your fingers you will see the pattern shown in the figure. What would you conclude from this activity?

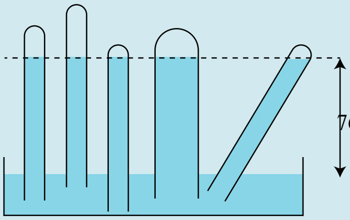


Figure 12. Demonstrating properties of liquid pressure

Applications of air pressure

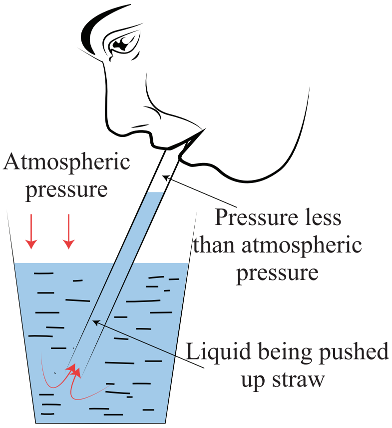


Figure 13. Straw

(i) Drinking water with a straw

Atmospheric pressure is also vital when using a drinking straw. When we suck through a straw, we are decreasing the pressure in the straw. This causes a pressure difference to be set up between the straw and the atmosphere. The atmospheric pressure acting on the surface of the liquid overcomes the pressure inside the straw. The pressure difference and hence the resulting force pushes the liquid up the straw.

(ii) Rubber sucker

When a rubber sucker is pressed into a smooth surface, usually glass, the air between the rubber sucker and the surface is forced out. This causes the space between the surface and the sucker to have low pressure. The external atmospheric pressure, which is much higher, then presses the sucker firmly against the surface, see Figure 14.

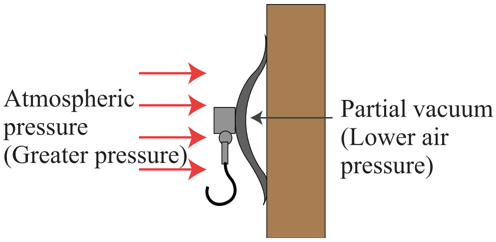


Figure 14. Rubber sucker

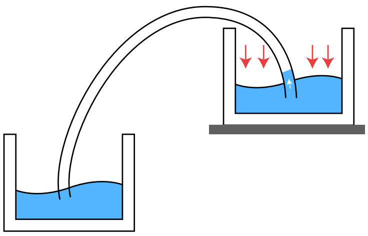


Figure 15. Siphon

(iii) A Siphon

Is a tube or pipe that allows liquid to flow from the higher level to the lower level. For example using a siphon, we can remove petrol from the petrol tank of a vehicle. The tube is first filled with the liquid you can do this by using your mouth and suck the liquid through in the tube and one end is placed in the liquid in the container. The other end is placed at a level which must be lower than the surface of the liquid in container. The atmospheric pressure at the top together with ground makes the liquid to flow down the tube .

ACTIVITY 7

The lift pump and force pump are also applications of atmospheric pressure. After searching through internet and reading books bring a report to your class how they work.

Gas pressure is dependent on the temperature, number of molecules, and the volume. We know that the temperature of the gas is proportional to the average kinetic energy of the molecules. By heating increase the temperature of the gas in a container. As a result, the collision between the molecules increases resulting in increased pressure in the gas.

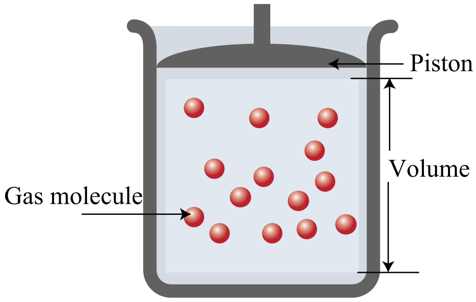


Figure 16. Temperature and pressure of a gas

The gas is therefore under greater pressure when its temperature is higher. This is why fires near sealed gas cylinders are extremely dangerous. If the cylinders heat up enough, their pressure will increase and they will explode.

(iv) Temperature and pressure in gases (Gas-Lussac's Law)

If the temperature of the gas is measured on the Kelvin scale, the pressure is proportional to the temperature (volume is kept constant). From this we can derive the equation

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

where: P_1 is the initial pressure, T_1 is the initial temperature, P_2 is the final pressure, and T_2 is the final temperature. This equation is true as long as the volume and mass of the gas are constant. The pressure versus temperature diagram shown in figure 17 demonstrates this fact.

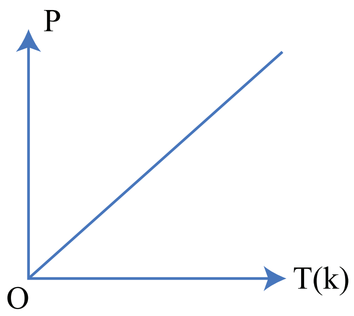


Figure 17. P vs. T diagram at constant volume

Volume and pressure in gases (Boyle's law)

Decreasing the volume of a gas increases the pressure of the gas. An example of this is when a gas is trapped in a cylinder by a piston. If the piston is pushed in, the gas particles will have less room to move as the volume the gas occupies has been decreased.

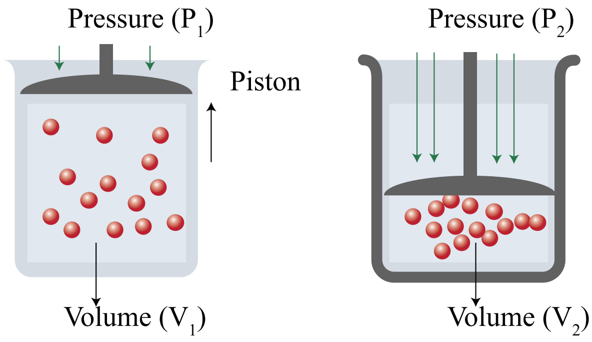


Figure 18. Voluume and pressure of a gas

Because the volume has decreased, the particles will collide more frequently with the walls of the container. Each time they collide with the walls they exert a force on them. More collisions mean more force, so the pressure will increase. This shows that the pressure of a gas is inversely proportional to its volume.

The relationship between the volume and pressure of a given amount of gas at constant temperature is summarized in the statement now known as **Boyle's law**:

The volume of a given amount of gas held at constant temperature is inversely proportional to the pressure under which it is measured. This is shown by the following equation - which is often called Boyle's law.

$$P_1V_1 = P_2V_2$$

where: P_1 is the initial pressure, V_1 is the initial volume, P_2 is the final pressure, and V_2 is the final volume

Note that volume is measured in meters cubed (m^3) and pressure in Pascal (Pa).

The pressure versus volume diagram shown in figure 19 demonstrates this fact.

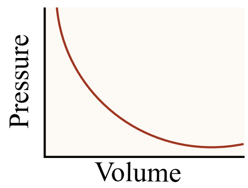


Figure 19. P vs. V diagram at constant temperature

Examples

A sealed syringe contains 10×10^{-6} m^3 of air at 1×10^5 Pa. The plunger is pushed until the volume of trapped air is 4×10^{-6} m^3. If there is no change in temperature what is the new pressure of the gas?

Solution: $V_1 = 10\times10^{-6}\,m^3$ $P_1 = 1\times10^5\,Pa$ $V_2 = 4\times10^{-6}\,m^3$ $P_1 = ?$

$$P_1V_1 = P_2V_2 \Rightarrow P_2 = \frac{P_1V_1}{V_2} = \frac{1\times10^5\,Pa\times10\times10^{-6}\,m^3}{4\times10^{-6}\,m^3}$$

$$P_2 = 2.5\times10^5\ Pa$$

Exercises

A car tyre contains air at 1.25×10^5 Pa when at a temperature of 27°C. Once the car has been running for a while, the temperature of the air in the tyre rises to 42°C. If the volume of the tyre does not change, what is the new pressure of the air in the tyre?

Activity 8

Demonstration on measurement of atmospheric pressure with inverted tube water barometer

Objective:

The objective of this experiment is to measure the pressure of the atmosphere by compressing a known volume of air with a water column. A tube containing air is inverted in another tube containing water.

Apparatus

Inverted tube, water barometer and a supply of water.

Theory

As the inner tube is lowered into the water, the water level rises thus compressing the air column and the various levels shown in the figure are measured allowing us to relate the changes in the volume of the air to the pressure on the air column.

The air captured in the tube can be considered an ideal gas. Then, since the amount of air is constant and the temperature can be assumed constant for the duration of the experiment, you have

$$P_1\ V_1 = P_2V_2\,,$$

If P_1 represents the original (atmospheric) pressure of the uncompressed air and V_1 the original volume of uncompressed air, then $V_1 = AL$, where A is the cross-sectional area of the inner inverted tube and L is its length. Therefore, if point 2 refers to the air-surface boundary inside the tube, then $V_2 = A[L-(y_m-y_b)]$ and the second equation becomes

$$P_{atm}AL = P_2A[L-(y_m-y_b)]$$

The pressure P_2 can also be related to the atmospheric pressure by

$$P_2 = P_{atm} + \rho_w g(y_s - y_m)$$

In this equation ρ_w is the density of water and $(y_s - y_m)$ is the difference between the levels of the water columns outside and inside the inner tube. Combining the last two equations gives

$$\rho_w g(y_s - y_m)[L - (y_m - y_b)] = P_{atm}(y_m - y_b)$$

This equation suggests that the atmospheric pressure can be measured by measuring the various levels and plotting the left hand side of the last equation as a function of the quantity $(y_m - y_b)$. The slope of the straight line graph is the atmospheric pressure.

Now give the left hand side of the last equation the symbol Z and rewrite the equation as

$$Z = P_{atm}(y_m - y_b)$$

Experimental procedure

1. Measure the length, L, of the inner tube which will contain the trapped air sample. Measure up to but not including the stopper.
2. Fill the outer tube with water up to an appropriate level. Around 45 cm high from the bottom will work best. It is suggested that you tape a meter stick by the side of the tube and use it to measure the water level for the entire experiment. It allows you to get more consistent measurements.
3. Lower the inner tube until the opening makes contact with the water surface. Let this be your first data point. Read the levels and record them in your data table. Note that the three levels are the same.
4. Now lower the tube below the water surface, read all the levels and record them in your data table. It is suggested that you lower the tube around 7 cm and read the levels to the nearest millimeter. It is very important to the success of this experiment that the levels should be read very carefully.
5. Repeat the above step by lowering the tube in the water and recording the levels until the inner tube is near the bottom of the water. This should give you either 6 or 7 data points.
6. Measure the density of tap water by filling a graduated cylinder with a certain volume of water (about 100 cm3). Measure the mass of the water and find the density by dividing the mass by the volume. Record the density in kg/m3.
7. Read the barometer hanging on the wall of the lab to get the actual atmospheric pressure.

Analysis

1. Complete the calculations indicated in the data table. In your lab report show a sample of these calculations.
2. Plot the quantity Z on the vertical axis and the quantity $(y_m - y_b)$ on the horizontal axis. Draw the best straight line fit for the data (do not connect the points). Calculate the slope of the line and give its units. The slope of the line represents the atmospheric pressure which is the result of this experiment. Record it in the results table.

3. Calculate the percent difference between the measured atmospheric pressure and the actual atmospheric pressure read from the lab barometer.

$$\%\text{difference} = \frac{\left(P_{\text{measured}} - P_{\text{actual}}\right)}{\frac{1}{2}\left(P_{\text{measured}} + P_{\text{actual}}\right)} \times 100\%$$

4. Write a conclusion summarizing your results. Comment on the success of this experiment.

Questions:

1. Is your result within 10% of the actual atmospheric pressure?
2. What do you think are the two most important sources of error in this experiment?

(v) Dimensional Analysis and its use in Physics

The dimension of a physical quantity refers to the fundamental units contained in it. Any quantity which can be measured in length units, are said to have the dimension of length (L). Any quantity which can be measured in mass units is said to have the dimensions of mass (M). Similarly any quantity which can be measured in time units have the dimension of time (T). The dimension of a quantity is written in square bracket as follows. $[\text{mass}] = \text{M}$, $[\text{length}] = \text{L}$, and $[\text{time}] = \text{T}$, where the square brackets mean "the dimension of the quantity within".

The derived units are based on the fundamental units and in many cases involve more than one fundamental unit. The dimension of derived quantities are expressed in general as $M^xL^yT^z$. Here x, y, and z indicate the number of times the unit of the particular fundamental physical quantity is involved.

Examples

Area: The unit of area is the product of two units of length, mm^2, or cm^2, or m^2. Thus the dimension of area is L^2, written as, $[\text{area}] = L^2$. Thus area has two dimensions of length.

Examples

Volume: The units of volume (mm^3, or cm^3, or m^3) is the cube of the unit of length. So the dimension of volume is L^3, written as, $[\text{volume}] = L^3$. Thus volume has three dimensions of length.

Examples

Density: Density is defined as mass divided by volume. Hence the unit of density is the unit of mass divided by the unit of volume. In SI units it is kg/m^3.Thus the dimension of density is the dimension of mass (M) divided by the dimension of volume (L^3), written as, $[\text{density}] = \frac{M}{L^3} = ML^{-3}$. Thus the dimension of density is 1 in mass, and –3 in length.

Such an expression for a physical quantity in terms of the **fundamental** physical quantities is called the **dimensional expression or equation**. If we consider only the right hand side of the equation, the expression is termed as **dimensional formula**. Thus, dimensional formula for density is, ML^{-3}, and that of volume is M^3. Some examples of physical quantities, their dimensions, and derived units are shown in table below.

Key Terms

- The dimension of a physical quantity refers to the fundamental units contained in it.
- The expression for a physical quantity in terms of the fundamental physical quantities is called the dimensional expression or equation.

Table 3 Dimensions and units of some common quantities.

Quantities	Dimensions	MKS Units
mass	M	kg
length (distance, height, etc.)	L	m
time	T	s
area	L^2	m^2
volume	L^3	m^3
density	ML^{-3}	$kg.m^{-3}$
Speed, velocity	LT^{-1}	$m.s^{-1}$
acceleration	LT^{-2}	$m.s^{-2}$
Force, weight	MLT^{-2}	$kg.m.s^{-2}$
Momentum	MLT^{-1}	$kg.m.s^{-1}$
pressure	$ML^{-1}T^{-2}$	$kg.m^{-1}.s^{-2}$
Work, energy	ML^2T^{-2}	$kg.m^2.s^{-2}$
power	ML^2T^{-3}	$kg.m^2.s^{-3}$

Exercises

Find the dimensional formulae for the following quantities.

(a) Speed,
(b) acceleration,
(c) Force,
(d) momentum,
(e) work,
(f) power and
(g) pressure.

Hint: Speed is distance traveled per unit time, acceleration is change in velocity per unit time, force is is the product of mass and acceleration, momentum is the product of mass and velocity, Work is force multiplied by distance moved, Power is the rate of work done, and pressure is force exerted per unit area.

Dimensionless quantities

Pure numbers and pure ratios are dimensionless. For example pure numbers like 1, 2, π are dimensionless. Similarly the ratio of two similar quantities like,

relative density = Density of object/Density of water, and

refractive index = Velocity of light in air/Velocity of light in medium are dimensionless.

ACTIVITY 9

Dimension/unit Jeopardy game

The table shown below contains answers (unit or dimension) to a question. Students must give the question for which the entry is an answer. Example, if you get M in the box, your answer will be what is the dimension of mass?

m/s	L^2	MLT^{-2}	ML^{-3}
LT^{-2}	m^3	ML^2T^{-2}	L^3
kg/m^3	MLT^{-1}	$kg.m.s^{-2}$	m^2
LT^{-1}	m/s^2	$kg.m^2.s^{-2}$	ML^2T^{-3}

Important properties of dimensions

Physical dimensions are treated as algebraic quantities. The following basic mathematical rules govern arithmetic operation in combining dimensions.

(i) Multiplication and division:

The dimension of a product of several variables is the product of the individual dimensions.

Example: The area of a rectangular surface is the product of its length and width. Since both are a type of length with dimension, L, the dimension of area is L^2.

(ii) Addition and subtraction:

It is not possible to add or subtract two or more quantities with different dimensions.

Example: You cannot add a length to a volume, or subtract a mass from a velocity. That is 10m/s plus 2 kg is meaningless.

The use of dimensions in physics

(i) To find the unit of a physical quantity in a given system of units

By writing the formula for the physical quantity we can find its dimensions. From the dimensional formula replacing M, by kilogram, L by meter and T by second we get the MKS unit of the quantity. However in some cases a specific SI unit may be assigned like the unit of force, newton (N), the unit of work, joule (J), and the unit of power, watt (W).

Examples

Work = Force × Displacement

So $[W] = [F] \times [s] = MLT^{-2} \times L = ML^2T^{-2}$

In the case of MKS (or SI) unit of work will then be $kg.m^2.s^{-2}$ which is called joule.

Exercises

1. From their dimensions determine the units of the following quantities.
   (a) momentum,
   (b) power.
2. The units in which force is expressed are kg m s^{-2}. What are the dimensions of force?

(ii) To find the unit of physical constant or coefficients

By substituting the dimensional formulae of all quantities in an equation, we can find the unit of the required constant or coefficient.

Examples

The spring constant. According to Hooke's law, $F = kx \Rightarrow k = \frac{F}{x}$. Substituting the dimension of force and extension we find that, $[k] = \frac{MLT^{-2}}{L} = MT^{-2}$.
Thus the SI unit of K is $kg.s^{-2}$.

To convert the unit of a physical quantity from one system to another

Physical quantity can be expressed as the product of numerical value (n) and unit (u) = nu. This product is constant

nu = constant

Let n_1 and u_1 represent the numerical value and unit of physical quantity in system 1.

n_2 and u_2 represent the numerical value and unit of physical quantity in system 2.

Then $n_1u_1 = n_2u_2$

$M_1L_1T_1$ be the fundamental unit in system 1 and $M_2L_2T_2$ be the fundamental unit in system 2.

The dimensions in mass, length and time in each system can be respectively by x, y, z.

$$u_1 = \left(M_1^xL_1^yT_1^z \text{ and } u_2 = M_2^xL_2^yT_2^z\right)$$

as we know $n_1u_1 = n_2u_2$

$$n_2 = n_1\frac{u_1}{u_2}$$

$$n_2 = n_1\frac{\left(M_1^xL_1^yT_1^z\right)}{\left(M_2^xL_2^yT_2^z\right)}$$

$$n_2 = n_1\left(\frac{M_1}{M_2}\right)^x\left(\frac{L_1}{L_2}\right)^y\left(\frac{T_1}{T_2}\right)^z$$

This equation can be used to find out the value of a physical quantity in the second or the new system, when its value in first system is known.

Examples

Convert 72 km/h to m/s.

$n_1 = 72$, $n_2 = ?$ $L_1 = 1\text{km}$, $T_1 = 1\text{hr}$, $L_2 = 1\text{m}$ and $T_2 = 1\text{s}$. Then substituting these values into the equation:

$$n_2 = 72\left[\left(\frac{1\text{km}}{1\text{m}}\right)^1\left(\frac{1\text{hr}}{1\text{s}}\right)^{-1}\right]$$

$$n_2 = 72\left[\left(\frac{1000\text{m}}{1\text{m}}\right)^1\left(\frac{3600\text{s}}{1\text{s}}\right)^{-1}\right]$$

$$n_2 = 72 \times 1000 \times \frac{1}{3600} = \frac{72000}{3600} = 20$$

Thus, $n_1u_1 = 72\text{km}/\text{h}$ and $n_2u_2 = 20\text{m}/\text{s}$

(iii) To check the dimensional correctness of an equation

This is based on the 'principle of homogeneity'. According to this principle, the dimensions of each term on both sides of an equation must be the same. For example, if $A + B = C$ is an equation in physics, the nature (dimensions) of A, B and C should be the same. That means, if A is a length, B must also be a length and the result of the addition of A and B must be expressed in length. That is every physical equation should be dimensionally balanced (consistent).

Examples

Let us check the dimensional correctness of the relation $v = u + at$.

Here 'u' represents the initial velocity, 'v' represents the final velocity, 'a' the acceleration and 't' the time.

Solution:

Dimensional formula of 'v' is LT^{-1}

Dimensional formula of 'u' is LT^{-1}

Dimensional formula of 'at' is $LT^{-2} \times T = LT^{-1}$

Because the dimensions of every term in the given equation are the same, the equation is dimensionally correct.

Examples

Check the dimensional correctness of the relation, $s = ut + \frac{1}{2}at^2$.

Here 'u' represents the initial velocity, 'a' the acceleration, 's' the displacement and 't' the time.

Solution:

Left hand side: Dimension of s, [s] = L

Right hand side: Dimension of ut, [ut] = velocity × time = length/time × time = $LT^{-1} \times T$ = L

Dimension of $\frac{1}{2}at^2$, $\left[\frac{1}{2}at^2\right]$ = $[at^2]$ = acceleration × $(time)^2$ = $\frac{velocity}{time} \times (time)^2$

$= \frac{lengt / time}{time} \times (time)^2 = LT^{-2} \times T^2 = L$

(Since ½ is a number, it is dimensionless)

Since the dimensions of L.H.S. = Dimensions of R.H.S., the formula is dimensionally correct.

Exercises

Using dimensional analysis, determine whether the following equations are dimensionally correct or not:

(a) $s = v_{av}t$

(b) $V_f = at$

(c) $h = \frac{1}{2}gt^2$

(d) $\rho = \frac{V}{m}$

(iv) To derive new equation

Dimensional analysis can also help you to derive the formula that you have forgotten.

Examples

Suppose you have forgotten the formula for speed. What you can recall is that it involves distance and time. The dimension for speed is L/T, the dimension for distance is M and the dimension for time is T. This means the equation for speed is distance travelled divided by time taken.

Limitations of dimensional analysis.

The following are limitations of dimensional analysis.

1. If dimensions are given, physical quantity may not be unique as many physical quantities have the same dimensions. For example if the dimensional formula of a physical quantity is ML^2T^{-2} it may be work or energy or torque.
2. Dimensional analysis gives no information about the dimensionless constants. For example in the equation $s = ut + \frac{1}{2}at^2$ the factor $\frac{1}{2}$ can not be deduced by the method of dimensions.
3. Dimensional analysis is used only if the physical quantities are the product or quotient of other quantities. It fails if a physical quantity is the sum or difference of other quantities.
4. For example, the equation, $s = ut + \frac{1}{2}at^2$, can't be derived by using this method. However, the dimensional correctness of these can be checked.
5. Dimensional analysis can't be applied to drive formula in cases where a physical quantity depends on more than three quantities. This is because by equating the powers of M, L and T, we can obtain only three dimensions.

Activity 10

Discuss the following concepts in group.

1. A formula that is physically correct, has to be also dimensionally correct. If a formula is dimensionally correct, it is not necessary that it is also physically correct.
2. A given quantity can only have one specific physical dimension. The converse, however, is not true: different physical quantities can have the same physical dimension.

Activity 11

Game- Dimension Clock

Objective: To practice the dimension of different physical quantities

Procedure:

(a) Cut a hardboard in a circular shape as shown in the figure

(b) Divide it into 12 equal parts as a clock is

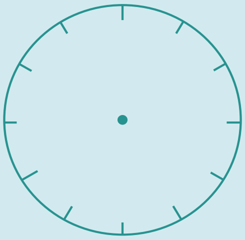
(c) Write the dimension of 12 different quantities on the place of time

(d) Rotate the circular board and let it to stop by itself

(e) Ask the student who rotate it the following two questions

1. To what quantity does the pointed dimension belong?
2. What is the SI unit of that quantity?

Repeat for another student



Exercises

1. The velocity v of a particle depends upon the time t according to the equation v = a + bt. Write the dimensions of a and b.
2. Suppose the displacements of an object moving in a straight line under uniform acceleration a is given as a function of time by the relation $s = kL^mT^n$, where k is a dimensionless constant. Use dimensional analysis to find the values of the powers m and n.
3. Determine the dimensions of the following quantities
   (a) linear momentum (mass × velocity)
   (b) work (force × displacement)
   (c) power (W/t)
   (d) pressure (force/area)
   (e) weight (gravitational force)
4. Define the following terms: (a) dimension, (b) Dimensional expression
5. What is the difference between dimension and unit?

(v) Measuring Instruments

The measurement of a physical quantity is done by using measuring instruments. In this section we will discuss how to measure length, mass, time, and temperature using their appropriate devices.

Least count

The smallest value that can be measured by the measuring instrument is called its **least count**. The least count is related to the precision of an instrument. An instrument that can measure smaller changes in a value relative to another instrument, has a smaller «least count» value and so is more precise. For example, the least count of a meter rule is 1mm, and the least count of a vernier caliper is 0.1 mm and least count of a micrometer is 0.01 mm.

Measuring length/distance

Length is the extent of space between two points. Length is measured with instruments such as meter rule, Vernier caliper, micrometer screw gauge, etc. Vernier caliper and a micrometer screw gauges are used to measure smaller length or distances.

Meter rule

A meter rule is the simplest length-measuring instrument. It has the great advantages of being cheap, convenient and simple to use. If it is 1m long it is known as a meter ruler which are divided into 100 equal parts called as centimeters (cm). Each cm is divided further in to 10 divisions which are called millimeters (mm). Hence least count of meter scale is 0.1cm or 1mm. So, a meter rule can measure up to 1mm as smallest reading.

Note:

The measurement error associated with each device is normally about half of the smallest dimension that the instrument is capable of measuring.

Reading a metric ruler

On a metric ruler, each individual line represents a millimeter (mm). The numbers on the ruler represent centimeters (cm). There are 10 millimeters for each centimeter. To read a metric ruler, each individual line represents 0.10 of a centimeter, or 1 millimeter.

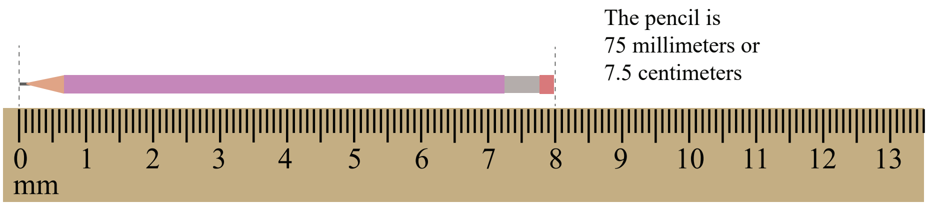


Figure 20. Reading a meter rule

KEY TERMS

- Meter rule, Vernier calipers, and micrometers are instruments for measuring distances or length.

The vernier caliper

The Vernier caliper was invented by a French Scientist Pierre Vernier (1580-1637) hence bearing his name Vernier. It is used to measure both the internal and external diameters as well as the depth of an object as shown in the diagram below.

Vernier caliper is used for measuring small lengths (0 – 15cm). These calipers come in handy in measuring the diameter of circular objects. The smallest distance that a vernier caliper can measure is 0.1 mm or 0.01 cm. To measure, gently grip the object with the straight edges of outside or inside jaws. The various parts of a Vernier caliper are shown in the figure below.

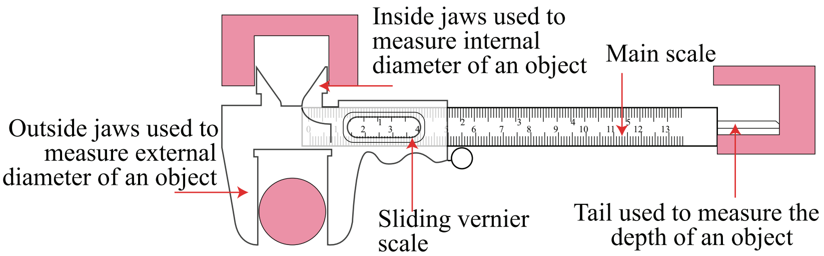


Figure 21. The Vernier caliper

A Vernier Caliper consists of a main scale and a sliding or vernier scale. The sliding scale (Vernier scale) is divided into 10 equal divisions and thus the least count of the instrument is 0.1 mm. Both the main scale and the sliding scale readings are taken into account while making a measurement. The left most mark on the Vernier scale is the zero mark. With the calipers closed, the zero mark of the Vernier scale coincides with the zero mark on the main scale for an error-free measurement.

To measure outer dimensions of an object, the object is placed between the jaws, which are then moved together until they secure the object. The screw clamp may then be tightened to ensure that the reading does not change while the scale is being read.

How to read a vernier caliper

- First Check for zero error.
- Place the object between the jaws of the caliper and close the jaws until the object is held firmly.
- Read the main scale reading before the zero (0) on the vernier scale.
- Find the markings on the vernier scale that coincides with the mark on the main scale.
- Multiply the reading of the vernier scale by the accuracy of the vernier scale which is 0.01cm.
- Finally add the reading scale to the main scale reading to obtain the final reading.

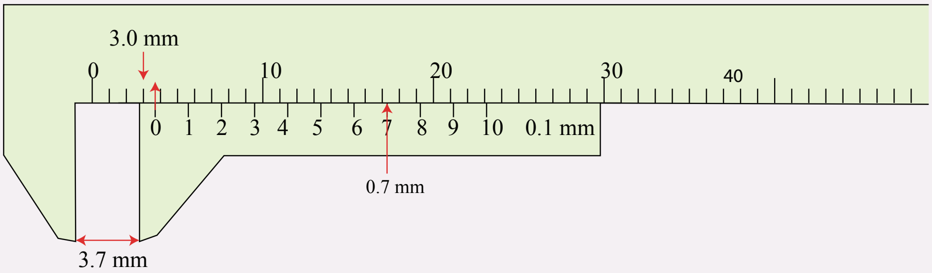
Total reading = M.S.R + (V.C × L.C).

Examples

What is the reading of the caliper shown in the figure?

Solution:

The main scale reading is the first reading on the main scale immediately to the left of the zero of the Vernier scale (3 mm), while the Vernier scale reading is the mark on the Vernier scale which exactly coincides with a mark on the main scale (7×0.01 mm = 0.7 mm). The reading is therefore: $3.0 + 0.7 = 3.7$ mm.



Zero Error: It occurs when jaws of Vernier caliper are fully closed but zeros of main scale and Vernier scale not coincides. This can be reduced by adding or subtracting according to whatever it is positive or negative error.

Digital caliper

The digital caliper consists of one fixed jaw, attached to a main beam, and one movable jaw that slides along the main beam. The distance between the two measurement jaws is displayed on the LED digital readout display located on the slider.

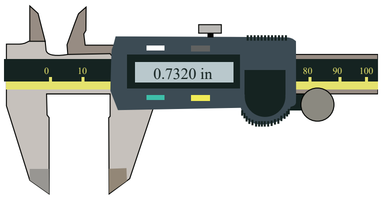


Figure 22. Digital vernier caliper

The micrometer screw gauge

A micrometer screw gauge is an instrument used for measuring very small length (0 and 2.5 cm) For example the diameter of the wire or thickness of a plate. The reading accuracy of the instrument is 0.001 cm or 0.01 mm. A micrometer screw gauge has two scales: main scale (on the sleeve) and the circular scale/vernier scale (on the thimble). Each division on the main scale is 1mm and the division on the vernier (thimble) scale is 0.01 mm. In order to measure the size of an object, the object is placed between the jaws and the thimble is rotated using the ratchet until the object is secured. Note that the ratchet knob must be used to secure the object firmly between the jaws, otherwise the instrument could be damaged or give an inconsistent reading. The manufacturer recommends 3 clicks of the ratchet before taking the reading.

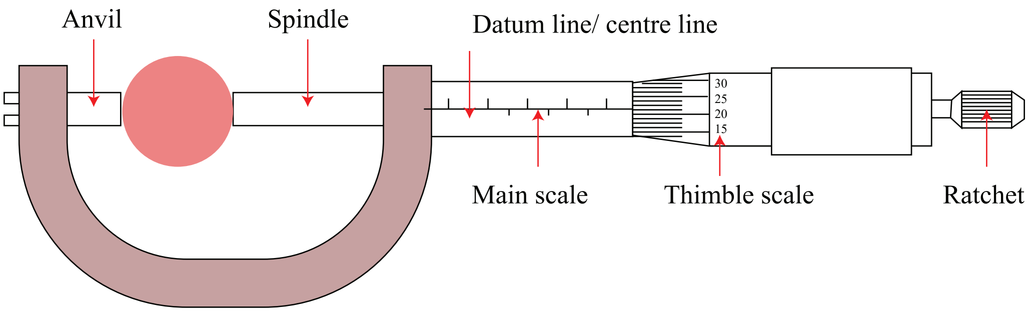


Figure 23. The micrometer screw gauge

Zero Error: When using Micrometer Screw Gauge, we have to first check for zero error. This is to check whether zero mark on thimble scale coincides with datum line on the main scale and reading on main scale is 0 when we are not measuring anything (anvil is in contact with spindle).

Accuracy of micrometer screw gauge

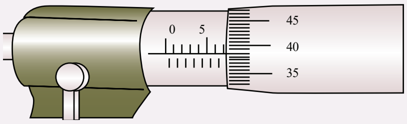
Accuracy of an instrument is the smallest distance that the instrument can measure correctly. Thus, the accuracy of a micrometer screw gauge is 0.01mm or 0.001cm.

Steps to follow when reading a micrometer screw gauge

- Close the jaws of the micrometer and check for a zero error.
- Place the object between anvil and spindle, and turn the thimble until the anvil and spindle grip the object. Then turn the ratchet until it starts to click for careful tightening.
- Read and record the reading of the main scale.
- Read and record the reading of the Vernier scale at the point where the main scale and the Vernier scale coincide.
- Multiply the reading of the Vernier scale by the accuracy of the Vernier scale which is 0.01mm.
- The actual measurement is then the sum of main scale reading and thimble scale reading, i.e Add the result of step 3 and 5 to get the final answer which is the reading of the Vernier calipers.

Examples

What is the readings of the micrometer meter screw gauges shown in the figures below?

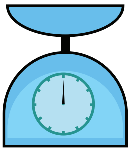


In the figure the last graduation visible to the left of the thimble is 7 mm and the thimble lines up with the main scale at 38 hundredths of a millimeter (0.38 mm); therefore, the reading is 7.38 mm.

Measuring mass or weight

Mass is a measure of matter contained in a body. The more the substance the more the mass will be. Mass is a measure of the inertia of the body. Thus the more mass the body has, the more it resists any effort to move it. The SI unit of mass is kilogram (kg). For small mass we use gram (g). To measure the mass of objects less than 1 gram, we can use milligram. To measure the mass of big objects we use quintal and tone.

Different types of balances are there, Beam balance, spring balance, table balance, platform balance, postal balance, triple balance are a few of the balances used for the measurement of mass, Figure 24


Top pan balance

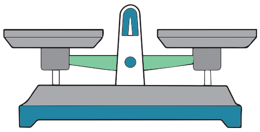
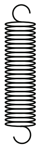
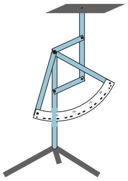
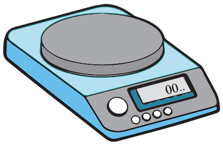


Table balance


Spring balance


Platform balance


Postal balance



Electronic balance

Figure 24. Instruments Used to Measure Mass

Beam balance

A beam balance is a device used to measure the mass of an object. It consists of a horizontal beam, supported at its center. The beam can move freely about its support and a pointer is attached to the center of the beam. Two similar pans are suspended at equal distances from the center of the beam by means of strings of equal lengths. The object whose mass is to be measured is kept on one pan and the standard known masses are kept on the other pan till the beam is horizontal and the pointer is vertical. Then the sum of the known masses gives the mass of the object.

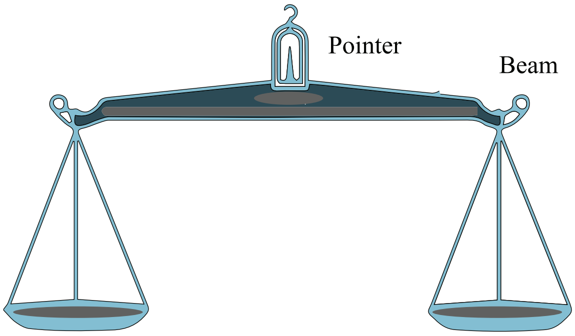


Figure 25. Beam balance

A beam balance works based on the principle of moments. According to the principle of moments at equilibrium, the anti-clockwise moment due to the weight of an object on the left pan of the beam is equal to the clockwise moment due to the standard weights on the right pan of the beam. Thus, although a balance actually measures the weight of an object, it can be graduated in units of mass rather than units of force.

KEY TERMS

- Beam balance, spring balance, table balance, platform balance, postal balance, triple balance are used for the measurement of mass.

Triple beam balance

The triple beam balance is an instrument used to measure the mass of various objects precisely. Such devices typically have a reading error of ±0.05 grams. Its name refers to its three beams, where the middle beam is the largest, the far beam of medium size, and the front beam the smallest. The difference in size of the beams indicates the difference in weights and reading scale that each beam measures. Typically, the reading scale of the middle beam reads in 100 gram increments, the far beam in 10 gram increments, and the front beam can read from 0 to 10 grams.

The object whose mass is being measured is placed on the pan on the left and the sliding weights are moved along the beams until the horizontal line on the right end of the beam is exactly aligned with the equilibrium line on the frame of the balance. When the two marks are in line, the sum of the masses on the three beams is exactly equal to the mass of the object on the pan.

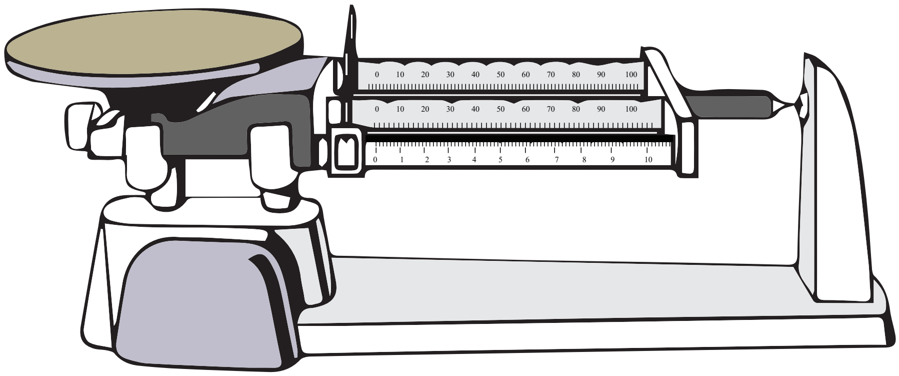


Figure 26. Triple beam balance

Spring balance

A spring balance (scale) is simply a spring fixed at one end with a hook to attach an object at the other. Spring scales measure the downward pull due to the earth's gravitational force of attraction, measured in units called newton. Other spring scales measure in grams (g). Some spring scales have the newton scale on one side and the gram scale on the other.

The spring balance is based on Hooke's law: which states that the weight of the body attached to the hook of the spring balance is directly proportional to the extension of the spring. Thus, the more the weight the more the extension and the less the weight the less the extension.

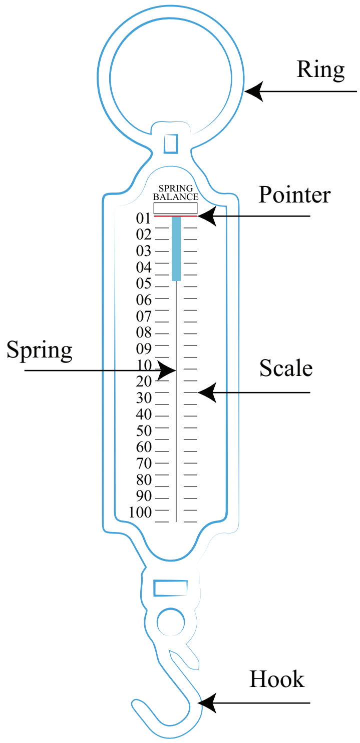
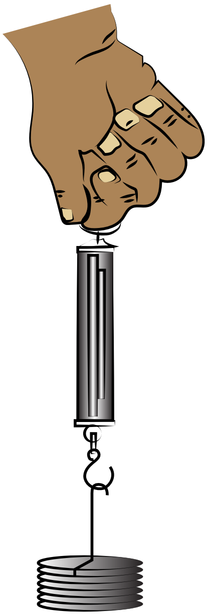


Figure 27. Spring Scale

ACTIVITY 12

In this activity, students assemble their own spring scales using brass fasteners and rubber bands.

Procedure



1. Hold the spring scale vertically. There is no force pulling its spring (apart from the weight of the hook}, so the reading must be zero. Make a mark on the blank strip that will be the 0 of your spring scale.
2. If you hang a 100-gramme mass from the spring scale the Earth will pull it down with a force of about 1 newton. That is the force that stretches the spring. Make a mark on the blank strip that will be the 1 of the scale.
3. Hang another 100 g mass from the spring scale. The force pulling the spring scale is now approximately 2 newton. Make a 2 newton mark on your spring scale.
4. Repeat this up to 10 newton. You have now 'calibrated' your spring scale so that it has a scale for taking measurements.
5. Take the masses off the spring scale and hang the unknown mass from it. Record the force of gravity (weight) that acts on this mass. You can now use your spring scale to measure any force, up to 10 newton.

Measuring time

Time is used to quantify the duration of events. Time is measured with a stop watch or clock.

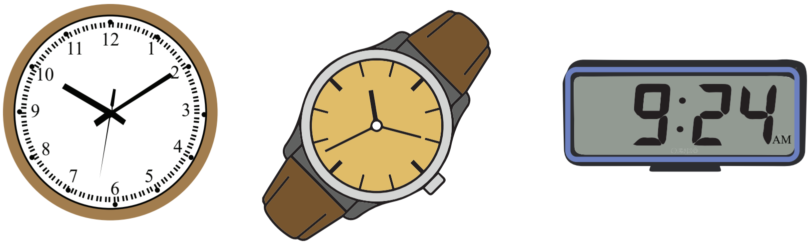


Figure 28. Time measuring Instruments

Stop watch (digital)

A stopwatch is an instrument used to measure time intervals. They are of two types: mechanical and digital. The least count of a mechanical stop watch is 0.1 s and of digital stop watch is of 0.01 s.

In manual timing, the clock is started and stopped by a person pressing a button. In fully automatic time, both starting and stopping are triggered automatically, by sensors. The timing functions are traditionally controlled by two buttons on the case. Pressing the top button starts the timer running, and pressing the button a second time stops it, leaving the elapsed time displayed. A press of the second button then resets the stopwatch to zero.

Digital electronic stopwatches are much more accurate than mechanical timepieces. Laboratory experiments and sporting events like sprints are good examples. The stopwatch function is also present as an additional function of many electronic devices such as cell phones, and computers.

Electronic balance

Electronic balance is an instrument used in the accurate measurement of mass of an object. Electronic balances allow the user to quickly and accurately measure the mass of a substance to a level of accuracy impossible for traditional balances to achieve. This is especially important in experiments that require precise amounts of each substance to achieve the desired results. The popularity of the electronic balance is also due to its extreme ease of use for any skill level.

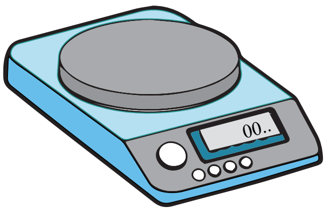


Figure 29. Electronic balance

Key Terms

- A stopwatch an instrument used to measure time intervals.
- Electronic balance is an instrument used in the accurate measurement of mass of an object.

Measuring temperature

Thermometer is a device used to measure the temperature of an object or place. The SI unit of temperature is Kelvin. Degree Celsius (°C) and degree Fahrenheit (°F) are other units of temperature. Thermometers are tubes of glass filled with mercury or alcohol. At the bottom of the tube is a wider part called the bulb. When the bulb is heated, the liquid in the bulb expands or gets larger, causing the liquid to rise in the tube. When the bulb is cooled, the liquid contracts or gets smaller, causing the liquid to fall in the tube. The bulb at the base of the thermometer should be immersed in the material to be measured. Thermometers could be analogue or digital, see Figure 30

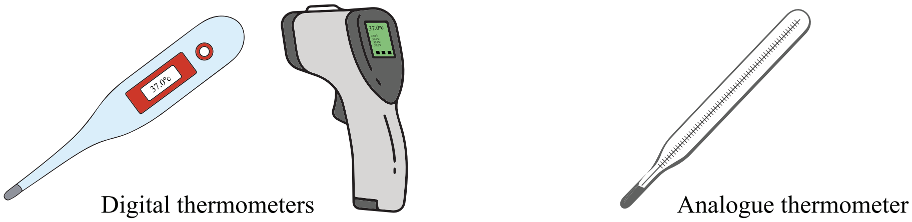


Figure 30. Temperature Measuring Devices

In using thermometer, hold the thermometer at the top, do not hold the bulb of a thermometer and do not let the bulb touch the glass.

Safety!!

For safety, never leave a child alone while you are using a thermometer, specially glass thermometer

Key Terms

- Thermometer is the device used to measure the temperature of an object or place.

Upon completion of this topic students will be able to:

- identify scalar and vector quantities

We measure physical quantities to describe them. But some of the physical quantities can't be completely described by their magnitude (size) alone. They need direction. For this reason physical quantities are classified into two categories: scalar quantities and vector quantities. Quantities that have only a magnitude and no direction are called **scalars**. Some examples of scalar quantities are mass, time, temperature, area, volume, density, distance, speed, work, energy and power.

On the other hand physical quantities which need both magnitude and direction for their description are called **vectors**. Some examples of vector quantities are: displacement, velocity, acceleration, force and momentum.

Key Terms

- Physical quantities that have only a magnitude and no direction are called scalars.
- Physical quantities which need both magnitude and direction for their description are called vectors.

Exercises

Classify the following quantities as scalars and vectors.

S. No	Quantity	Classification (Scalar or vector)
1	5 m	
2	30 m/s, East	
3	10 seconds	
4	20 degree Celsius	
5	4000 joule	
6	5 Km, North	

Summary

Major Branches of Physics

- Classical physics
  - Machanics
  - Thermodynamics
  - Optics
  - Electromagnetism
  - Acoustics
- Modern physics
  - Quantum physics
  - Atomic physics
  - Nuclear physics
  - Relativity

- The comparison of any physical quantity with its standard unit is called measurement.
- Systems of measurement: the metric system, the British imperial and the United States Customary systems
- Physical Quantities which cannot be expressed in terms of any other quantity are called fundamental.
- Physical quantities which depend on one or more fundamental quantities for their measurements are known as derived quantities.
- Words or symbols that represent the factors of ten are called prefixes.
- A conversion factor is a fraction that is equal to one used to convert a unit from one system to another.

- The number of figures required to specify a certain measurement are called significant figure.
- Accuracy is how close a measurement is to the true or accepted value.
- Precision is the degree of consistency and agreement among independent measurements of the same quantity.
- Uncertainty is a quantitative measure of how much your measured values deviate from a standard or expected value.
- Measurement error is the difference between a measured value and the true value for that measurement.
- Systematic errors are errors that are consistently in the same direction, they are one-sided errors.
- Random errors are errors that cause your measurements to be sometimes above the accepted value and sometimes below the accepted value.
- Pressure is defined as the amount of force exerted (thrust) on a surface per unit area.
- The density (ρ) of matter can be defined mathematically as the mass divided by the volume.
- The relative density (RD) or specific gravity (SG) of a substance is the ratio of density of a substance to the density of water at 4^oC.
- The pressure of a static (non-flowing) liquid is: $Pressure = \rho gh$
- The total pressure, or absolute pressure, is thus the sum of gauge pressure and atmospheric pressure: $P_{total} = P_{atm} + \rho hg$
- Pascal's Principle: "A change in pressure applied to an enclosed fluid is transmitted unchanged to every point within the fluid"
- The pressure due to the sea of air which surrounds us is called atmospheric pressure. Atmospheric pressure decreases with increasing height.
- Atmospheric pressure is measured using an instrument called a barometer.
- A manometer measures the pressure acting on a column of fluid. It is made from a U-shaped tube open on both ends.
- The relationship between temperature and pressure of a gas: $\frac{P_1}{T_1} = \frac{P_2}{T_2}$
- The relationship between volume and pressure of a gas: $P_1V_1 = P_2V_2$
- The dimension of a physical quantity refers to the fundamental units contained in it.

- The expression for a physical quantity in terms of the fundamental physical quantities is called the dimensional expression or equation.
- Meter rule, Vernier calipers, and micrometers are instruments for measuring distances or length.
- Beam balance, spring balance, table balance, platform balance, postal balance, triple balance are used for the measurement of mass.
- A stopwatch an instrument used to measure time intervals.
- Electronic balance is an instrument used in the accurate measurement of mass of an object.
- Thermometer is the device used to measure the temperature of an object or place.
- Physical quantities that have only a magnitude and no direction are called scalars.
- Physical quantities which need both magnitude and direction for their description are called vectors.
- A method of writing very big and very small numbers using the powers of ten is known as scientific notation.

Exercises

1. What is the difference between Metric System and English System?
2. What are the Conversion Factors?
3. Express each of the following numbers in exponential notation with two significant figures:
   (a) 0.03344
   (b) 22086
   (c) 0.0000000651
4. How many significant figures are contained in each of the following measurements?
   (a) 38.7 g
   (b) 2×10^{18} m
   (c) 9.74150×10^{-4} J
   (d) 0.0613 cm^3
   (e) 17.0 kg
   (f) 0.01400 g/cm^3
5. Round off each of the following numbers to two significant figures:
   (a) 0.436
   (b) 27.2
   (c) 1.497×10^{-3}
   (d) 0.445
6. Perform the following calculations and report each answer with the correct number of significant figures.
   (a) 5.63×7.4
   (b) 8119×0.000023
   (c) $14.98 + 27.340 + 84.7593$

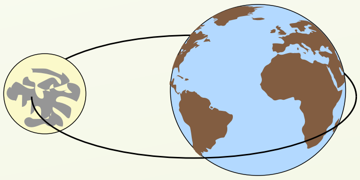
7. Classify the following sets of measurements as accurate, precise, both, or neither.
   (a) Four measurements of mass: 17.27 g, 13.05 g, 19.46 g, 16.92 g
   (b) Four measurements of volume: 27.02 mL, 26.99 mL, 26.97 mL, 27.01 mL
8. Why do the load carrying heavy vehicles have large number of wheels?
9. How much pressure do we carry on our heads? Why don't we feel it?
10. A box weighs 100N and its base has an area of 2m^2. What pressure does it exert on the ground?
11. In a hydraulic press a force of 20 N is applied to a piston of area 0.20 m^2. The area of the other piston is 2.0 m^2. What is,
    (a) the pressure transmitted through the liquid,
    (b) the force on the other piston?
12. What is the pressure 100 m below the surface of sea water of density 1150 kg/m^3?
13. The depth of a pond is 1.5 m. Calculate the pressure caused by the water at the bottom of the pond.
14. A tank with length 5 m, width 3 m and depth 2 m is filled with a liquid of density 800 kg.m^{-3}.
    (a) What is the pressure at the bottom of the tank due to the liquid?
    (b) What is the force acting on the bottom of the tank due to that pressure?

P10CH02

CHAPTER 2

VELOCITY AND ACCELERATION

Chapter Contents



Chapter Outcomes

You will be able to:

- recognize the various types of motion, their applications and the various forms in which forces affect the state of a body.

Introduction

This unit deals with how the physical quantities such as displacement, velocity, acceleration and time are related each other quantitatively. Formulas are employed in all uniform and accelerated motions. However, graphical methods are applied for uniform motion only. It was believed by Philosophers of antiquity that an unbalanced force requires to set an object in accelerated or uniform motion. Later Sir Isaac Newton clarified which types of motions require unbalanced force and which ones can be done without any intervention of net force. The other important observation of Newton was that forces always exist in pairs. Newton described all these phenomena in his three laws which are the concern of this unit. According to Newton's laws, in the absence of unbalanced force an object can move with constant velocity but it requires net force to accelerate. So why do other objects accelerate towards earth's center when they are released freely? This question is again answered by another universal law known as Newton's law of universal gravitation, which was again an outstanding finding of Sir Isaac Newton. This law is treated around the end of the unit.

Upon completion of this topic you will be able to:

- analyze motion (Uniformly accelerated), and
- apply the basic equations of motion (Interpret the motion graph).

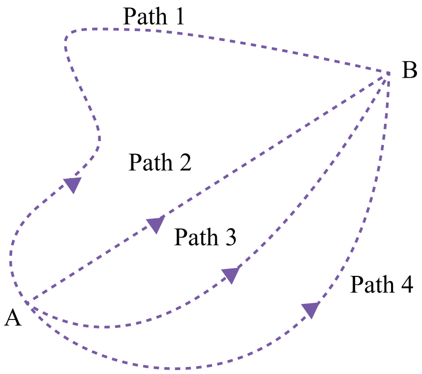
We can define motion as the change of position of an object with respect to time. A penny falling off a table, harvest oscillating by a blowing wind, water flowing in a river, etc., exhibits motion. We usually see objects moving along different types of paths. Thus, we can classify motion based on the types of paths that moving objects may follow. There are also different types of changes in the state of motion of objects. Therefore, quantifying motion is another important aspect to be studied. This topic deals with types of motion, elements of motion, changes in state of motion and the dynamics causing the change in the state of motion (force).

A. Elements of Motion

To understand the notion of the motion of an object, you should first be able to describe its position. The position of an object refers to where it is located at any particular time relative to a convenient observation point, known as frame of reference, or reference frame. Position can be described on coordinate system, where the origins being the reference frame. You cannot describe motion without specifying reference frame as well. When you are moving along a street, you can perceive, or even can measure elements of your motion with respect to trees, buildings, or the surrounding as a whole, which can be used as reference frames to describe your movement.

The motion of an object is defined as the change in its position in a given interval of time with respect to a certain reference in its surroundings. The motion of an object can be described in terms of physical quantities; namely, distance, displacement, speed, velocity, time, and acceleration.

(i) Distance and Displacement



Distance and displacement are two quantities that seem to mean the same but are distinctly different with different meanings and definitions.

Figure 1. Three possible paths of motion

Suppose an object moves from position A to position B, as shown in Figure 1. You can easily see that the object has infinite alternative paths to travel from A to B. The distance travelled by the object depends on the path it follows. To measure the total distance traveled by the object, you should know its path. distance is a measure of the path length of a journey an object has covered during its motion. Distance is a scalar quantity and its SI unit is meter, m.

Key Terms

- Position is location of an object at any particular time relative to a reference frame.
- Displacement is distance at a spacific direction

However, displacement is the measure of how far an object is out of its initial position displacement is a vector quantity directed from the starting towards the final positions and hence it does not depend on the path followed by the object. That is, the magnitude of the displacement is a measure of the shortest distance between the starting and destination points. In Figure 1, the magnitude of the displacement is equal to the distance if the motion is along path 2..

When an object exhibits one dimensional motion, a single axis (x-axis) can be used as the coordinate system to define its motion. In this case, you can ignore the vector notations such as arrowed symbols and indicate directions by positive (+) and negative (-) signs.

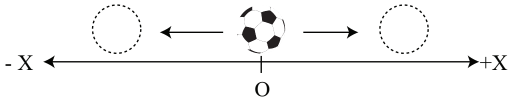


Figure 2. Graph to show positive and negative position in one dimensional motion

Consider the linear motion of a ball shown in Figure 2. If the ball starts at the origin (x = 0),

- position to the left of the origin is negative and that to the right is positive.
- direction of motion towards the negative x-axis is negative and that towards the positive x-axis is positive.

KEY TERMS

- Instantaneous speed, speed at a given instant in time
- Instantaneous velocity, velocity at a given instant in time

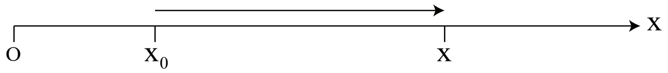


Figure 3. Representation of position and displacement

When we use a coordinate system, the origin becomes the reference point. Suppose an object moves from an initial position x_0 to an arbitrary position x as shown in Figure 3. The displacement of the object given by

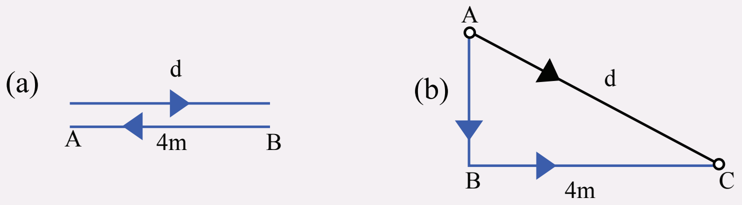
$$\vec{d} = \Delta\vec{x} = \vec{x} - \vec{x}_0$$

Since the motion is one dimensional, we can rewrite the above equation as

$$d = \Delta x = x - x_0$$

Examples

In the figure below, diagrams are given to show the motion of an object from A to B in two different situations. Determine the magnitude of the displacement in each case.



Solution:

In case (a),the object moved from A to B and returned to A again. The total distance d is

$$d = \overline{AB} + \overline{BA} = 4m + 4m = 8m$$

The measure of the total path length is 8m.

The total displacement 4 m + (− 4 m) = 4 m − 4 m = 0,

$$\vec{d} = \overrightarrow{AB} + \overrightarrow{BA} = 4m - 4m = 0$$

Displacement is the shortest distance between the initial and final position. In this case, both are the same (the object is returned to its initial position), and hence, displacement is zero.

In case (b), the total distance the object traveled is,

$$d = \overline{AB} + \overline{BC} = 3m + 4m = 7m$$

The magnitude of the displacement can be calculated using the Pythagoras theorem as

$$\left|\vec{d}\right| = \left|\overrightarrow{AC}\right| = \sqrt{\left|\overrightarrow{AB}\right|^2 + \left|\overrightarrow{BC}\right|^2}$$

$$\left|\vec{d}\right| = \sqrt{(3m)^2 + (4m)^2} = 5m$$

You can also determine the direction of the displacement using trigonometry.

(ii) Speed, Velocity and Acceleration

Once the reference frame for the motion of an object is selected, the object's motion can be easily defined in terms of speed, velocity and acceleration.

What is speed?

The speed of an object tells how fast it is moving. Speed is a scalar quantity, which is defined as the rate of distance traveled. A moving object may not always maintain a constant fastness, rather it varies with time. Therefore, we define average speed.

Average speed, v, is defined as the total distance traveled, s, divide by the total time, t, taken to cover the distance. The mathematical form of this definition is given by

$$v = \frac{s}{t}$$

The SI unit of time is second (s), the SI unit of distance is meter (m) and hence the SI unit of speed becomes meters per second (m/s). Other non-SI units of speed are kilometers per hour (km/h), miles per hour (mph), etc.

Instantaneous speed

We can find the average speed of a car by simply dividing the total distance traveled by the total time taken. In this case, the speedometer a car reads the speed for every instant of time. Thus, the speed of the car at a specific instant in time, however, is called its instantaneous speed. A car's speedometer reads its instantaneous speed.

Examples

A car started traveling at 9:00:00 AM and ended its journey at 11:00:00 AM. The average speed of the car was 50 km/h. What was the total distance covered by the car?

Solution: $t_0 = 9$ hr, $t_f = 11$ hr, $v = 50$ km/hr

The total time, t, elapsed to cover the given distance can be calculated as the difference Δt between the ending time t_f and the beginning time (t_0) as

$t = \Delta t = t_f - t_0 = 11\text{ hr} - 9\text{ hr} = 2\text{ hr}$

The total distance covered is

$s = vt = 50\text{ km/hr} \times 2\text{ hr} = 100\text{ km/hr}$

Examples

A boy traveled from his home to his school along a straight line and returned home after 30 minutes. If the distance of the school from his home along this path is 2km, what is the average speed of the boy?

Solution: $d = 2\times2\text{ km} = 4\text{ km}$, $t = 30\text{ min} = 0.5\text{ hr}$

The average speed, v, is

$$v = \frac{d}{t} = \frac{4\text{km}}{0.5\text{hr}} = 8\text{km/hr}$$

During a 30 minute round trip from home to school then from school to home, the total distance traveled is 4 km. The average speed is 8 km/h. Since there was no net change in position, the displacement for the round trip is zero.

Examples

A cyclist rides in her training field with an average speed of 8 m/s. The distance she has traveled is 20km. How long did it take her to ride this distance?

Solution: $d = 20\text{ km} = 20000\text{ m}$, $v = 8\text{ m/s}$

The desired time is derived from $v = d/t$ as

$$t = \frac{d}{v} = \frac{20000\text{m}}{8\text{m/s}}$$

$$t = 2500\text{s} = 41.67\text{min}$$

What is velocity?

Velocity can be defined as the rate of change of displacement. Velocity may not always be constant it may vary with time. In this case, we define average velocity. If an object travels a total displacement, Δx, in a time interval, Δt, its average velocity, $\vec{v}$, is defined as

$$\vec{v} = \frac{\Delta \vec{x}}{\Delta t}$$

Since displacement is a vector, velocity is also a vector quantity. It is basically speed in a specific direction. The SI unit of velocity is meter per second (m/s), which is the same as the unit of speed.

In the previous lesson, you have learnt that distance traveled can be different from the magnitude of displacement. In the same way, speed can be different from the magnitude of velocity. For example, you run to a shop and return home in 30 minutes. If the total distance you traveled was 1.6 km, then your average speed was 3.2 km/h. Your average velocity, however, was zero because your displacement for the round trip was zero.

Instantaneous velocity

The average velocity is defined as the rate of change total displacement. However, during the course of the journey, the velocity varies with time either in magnitude, or in direction or in both magnitude and direction. The quantity that tells us how fast an object is moving anywhere at a specific instant of time is the instantaneous velocity, usually called simply velocity.

Examples

A trucker drives along a straight highway with an average velocity of 15.0 m/s eastward for 0.25 h. She then pauses before driving with an average velocity of 10.0 m/s east. What is the trucker's total displacement from her starting point?

Solution: $t_1 = 0.25$ hr = 900s, $t_2 = 0.5$ hr = 1800s, $v_1 = 15$ m/s, $v_2 = 10$ m/s

Since all vectors are in the same directions, we do not need to include it in every step as long as it doesn't change our calculation. The total displacement is

$$d = d_1 + d_2 = v_1 t_1 + v_2 t_2$$

$$d = 15\ m/s \times 900s + 10\ m/s \times 1800s = 31.5km \ \backslash$$

$$\vec{d} = 31.5km,\ Eastward$$

Uniform Motion

Uniform motion is defined as the motion of an object in which the object travels with a constant speed along a straight line. We say the object is moving with a constant speed if it covers equal distances in equal intervals of time.

In a uniform motion, the instantaneous velocity at any time over the entire trip is the same as the average speed. If an object starts from an initial position x_0 and travels at a constant velocity, v, then its position, x, at any time, t, is given by

$$x = x_0 + vt$$

Then, the displacement at any time t, becomes

$$d = x - x_0 = vt$$

KEY TERMS

- Uniform motion, motion at a steady speed in a straight line

Examples

A bird flies from one branch to another with a constant velocity of 8 m/s in the positive x-direction. If it started at x_0 = 5m and flew for 4 seconds, determine

(a) the final position, and

(b) the total displacement.

Solution: t = 4 s, x_0 = 5m, v = 8 m/s

(a) The position of the object is measured from the origin of the coordinate system (x = 0). The final position is,

$$x = x_0 + vt = 5m + 8m/s \times 4s$$

$$x = 37m$$

(b) The positive displacement indicates, the final position of the object is to the right of its initial position.

The total displacement is $d = vt = 8m/s \times 4s = 32m$

Examples

In the figure below, a boy walks from point O to point B in 5 seconds and then walks back to point A in 3 seconds. What are the average speed and average velocity of the boy

(a) from O to B, and

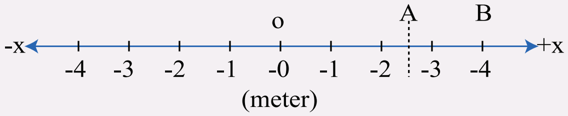
(b) from O to B and back to A?

Solution: t_1 = 5 s, t_2 = 3 s, x_0 = 0, x_1 = 4 m, x_2 = 2.5 m

The average speed depends only on the magnitude of distance, whereas the average velocity depends on the magnitude and direction of displacement.

(a) From O to B: Average speed,

$$v = \frac{x_1 - x_0}{t_1} = \frac{4m - 0}{5s} = 0.8m/s$$



Average velocity,

$$v = \frac{x_1 - x_0}{t_1} = \frac{+4m - 0}{5s} = +0.8m/s$$

(b) From O to B and back to A: Average speed,

$$v = \frac{|x_1 - x_0| + |x_1 - x_2|}{t_1 + t_2} = \frac{|4m| + |2.5m - 4m|}{5s + 3s}$$

$$v = \frac{5.5m}{8s} = 0.69m/s$$

Average velocity,

$$v = \frac{(x_1 - x_0) + (x_1 - x_2)}{t_1 + t_2} = \frac{(4m - 0) + (2.5m - 4m)}{5s + 3s}$$

$$v = \frac{2.5m}{8s} = 0.31m/s$$

What is acceleration?

During the course of any motion, the velocity of the moving object may change in time. Acceleration measures the rate of change in velocity. The velocity of the object may not change at a constant rate. In this case, we define average acceleration. Since acceleration is the change in velocity (not change in speed) per unit time, it is a vector quantity. If the velocity of an object changes by $\Delta\vec{v}$, within a time interval, Δt, the average acceleration, $\vec{a}_{av}$, is defined mathematically as

$$\vec{a}_{av} = \frac{\Delta\vec{v}}{\Delta t}$$

The SI unit of velocity is meters per second (m/s), the SI unit of time is seconds (s), and hence the SI unit of acceleration becomes meters per second per second (m/s/s, or usually written as m/s^2).

KEY TERMS

- Acceleration, the rate of change of velocity.

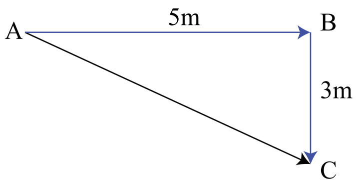
The faster the velocity changes, the greater the acceleration. The change in velocity may be change in magnitude, in direction or in both magnitude and direction. That is, we say the velocity is changing when

- the magnitude of the velocity increases,
- the magnitude of the velocity decreases,
- the direction of motion changes, or
- both magnitude and direction of the velocity changes.

If the velocity of the object is decreasing in time, the associated acceleration is negative and is commonly called retardation, or deceleration.

Exercises

1. What is motion?
2. What is the difference between distance and displacement?
3. Can displacement be zero while the distance traveled being non-zero?
4. In the figure shown below, a rat ran from point A to point B and then to point C.

   (a) Determine the total distance traveled by the rat.

   (b) What is the displacement of the rat?
5. A student travels 2 km due North but then back-tracks to South for 1.5 km to pick up a friend. What is the student's total displacement?
6. A hesitant car travels 200 m northwards, and then 50 m southward then 70m back to north. What are the car's distance and displacement?
7. Imagine a coach darting around a soccer field for several hours. Can his displacement from his initial position ever be larger than the total distance he traveled?
8. How long does it take for the car to cover a distance of 50 km, if its average speed is 10m/s?
9. A woman drives with an average velocity of 20 m/s Eastward for half an hour and then drives with an average velocity of 5 m/s to the same direction for 0.4 hours. What is her average velocity?
10. What does 1m/s/s mean?
11. Can you tell how fast an object is moving, given only the magnitude of acceleration?
12. Is it possible to have non-zero acceleration while the magnitude of speed kept the constant?

(i) Uniform acceleration

If the velocity of an object, moving along a straight line, changes equally in equal intervals of time, then the acceleration is constant and usually called uniform acceleration. Motion with a **uniform acceleration** is said to be uniformly accelerated motion. From the definition of uniformly accelerated motion, you may understand that the uniform acceleration can be witnessed in a straight line motion. Motion of a freely falling body near earth's surface, is an example of uniformly accelerated.

Other examples of uniformly accelerated motions are:

- a ball rolling down an inclined ramp of uniform roughness.
- a boy, riding a bicycle on the slope where both the pedals are engaged.
- a kid sliding down the slider, etc...

(ii) Equations of Uniformly Accelerated Motion

In a uniformly accelerated motion, the acceleration, a, is constant. Since the motion is in a straight line, direction can be determined by directional adjectives "–" and "+" and we can simply use lightface symbols. Suppose, in a uniformly accelerated motion, the velocity is changed from v_0 to v as the time changes from $t_0 = 0$ to t, respectively. The acceleration, a, is defined as

$$a = \frac{v - v_0}{t}$$

where,

- v_0 is the initial velocity of the body
- a is the acceleration of the body
- t is the time interval

The velocity of the object can be derived from the above equation to be

$$v = v_0 + at$$

Since the velocity changes linearly with time, the average velocity can be calculated by

$$v_{av} = \frac{v_0 + v}{2}$$

The total displacement, $s = v_{av}t$ is, then

$$s = \left(\frac{v_0 + v}{2}\right)t$$

Combining this with $v = v_0 + at$, we will have two alternative equations given as

$$s = v_0 t + \frac{1}{2} at^2 \text{ and } v^2 = v_0^2 + 2as$$

Characteristics of uniformly accelerated motion

- If the direction of both acceleration and the change in velocity is the same then it will result in positive acceleration.
- At the same time if the direction of acceleration and the change in velocity is different or in the opposite direction then it will result in negative acceleration known as retardation or deceleration.

Examples

A man, starting at rest, travels at a constant acceleration of 2 m/s^2 through a distance of 100m. How long does it take for the man to cover this distance?

Solution: $a = 2\ m/s^2$, $s = 100m$

Since the man started his journey from rest, then his initial velocity is zero $(v_0 = 0)$. Now, we have to calculate the time taken to cover the given distance.

$$s = v_0 t + \frac{1}{2} at^2$$

Substituting the given values we get

$$100m = 0 + \frac{1}{2}(2m/s^2)t^2$$

$$\text{or, } t = \pm\sqrt{100s^2}$$

Since there is no negative time, we take the positive value. That is,

$$t = 10s$$

Examples

A car, starting from rest, accelerated at 3 m/s^2 for 10 seconds. What will be the velocity of the car at the end of 10 seconds?

Solution: $a = 3\ m/s^2$, $t = 10\ s$, $v_0 = 0$

The velocity at t = 10 s, can be calculated as

$$v = v_0 + at = 0 + (3m/s^2)(10s)$$

$$v = 30m/s$$

Therefore, the velocity of the car at the end of 10 seconds is 20 m/s.

Examples

The velocity of a marble, pushed down a slope with a velocity of 9 m/s, is increased to 10 m/s at the end of the slide. If it were accelerating at 5 m/s^2, determine the length of the slide that the marble has traveled.

Solution: a = 5 m/s^2, v_0 = 9 m/s, v = 10 m/s

The distance traveled by the marble is calculated from equation

$$v^2 = v_0^2 + 2as$$

After some rearrangements, we obtain

$$s = \frac{v^2 - v_0^2}{2a} = \frac{(10m/s)^2 - (9m/s)^2}{2(5m/s^2)} = 1.9m$$

Exercises

1. What will be the acceleration of an object which moves with uniform velocity?
2. For the velocity against time tables given below, answer the following questions.
   (a) Do these tables represent uniformly accelerated motions?
   (b) What is the difference between the resulting accelerations in the two tables?

A	
Time(s)	Velocity (m/s)
0	1
1	3
2	5
3	7
4	9

B	
Time(s)	Velocity (m/s)
0	9
1	7
2	5
3	3
4	1

3. An airplane initially cruising westward at 400 m/s when a gust of wind blows against the aircraft causing it to slow down with a constant acceleration of magnitude 10 m/s^2.
   (a) What will the speed of the aircraft be after the wind has blown for 4 seconds?
   (b) If the wind stays for 5 seconds, how far does the aircraft fly during this time?
4. A nervous lion starts from rest and speeds up uniformly to 10 m/s within a time of 4 seconds. What is the magnitude of the average acceleration of the lion?

5. A cyclist, initially riding a bicycle with a velocity of 6m/s along a straight high way, started speeding up at a constant rate through a displacement of 100m. If the final velocity was 10 m/s, what was the acceleration?

2.3 Graphical Analysis of Uniform Motion (Using Standard Graph Sheets)

The construction of graphs is a very important technique in physics. Graphs provide a compact and efficient way of displaying the functional relationship between two parameters and of summarizing experimental results. When graphs are required and if you are instructed to "plot y vs. x" (where x and y are variables), then by convention, y (the dependent variable), should be plotted along the vertical axis (ordinate) and x (the independent variable) should be along the horizontal axis (abscissa).

Graphs that are intended to provide numerical information should always be drawn on squared or cross-section graph paper, 1 cm × 1 cm, with 10 subdivisions per cm. Each coordinate axis of a graph should be labeled with the word or symbol for the variable plotted along that axis and the units (in parentheses) in which the variable is plotted as shown in Figure 4.

Scales should be chosen in such a way that data are easy to plot and easy to read. On coordinate paper, every 5th and/or 10th line is slightly heavier than other lines; such a major division-line should always represent a decimal multiple of 1, 2, or 5 (e.g., 0, l, 2, 0.05, 20, 500, etc.). Enter data points on a graph by placing a small dot at the coordinates of the point and then drawing a small circle around the point.

Obtaining the Slope and Intercept on Straight-line Graphs of a uniform motion

In uniform motion, there is a linear relationship between graphed quantities, such as displacement – time, and velocity – time. In these situations, you will be asked to fit a straight line to the data points and to determine the slope and y-intercept from the graph.

The slope of a straight line is computed by dividing the 'rise' by the 'run' of the line. For the 'run', choose two convenient scale locations along the horizontal axis near the ends of the line, and draw light vertical lines to intersect the plotted line. Read off the positions of these intersections along the vertical axis and subtract to obtain the 'rise'. Always report the calculated slope on the graph itself. You may find it helpful to label 'rise' and 'run' and intersection points at least until your graphing technique is well developed. When you are asked to determine the intercept with the y-axis, label the intercept where the plotted line intersects the vertical axis (assuming that the vertical axis is located at the '0' position along the horizontal scale).

Consider two physical variables, x and y that we expect to be connected by a linear relationship:

$$y = a + bx.$$

A graph of y vs. x should be a straight line which has a slope of b and intersects the y-axis at the intercept y = a.

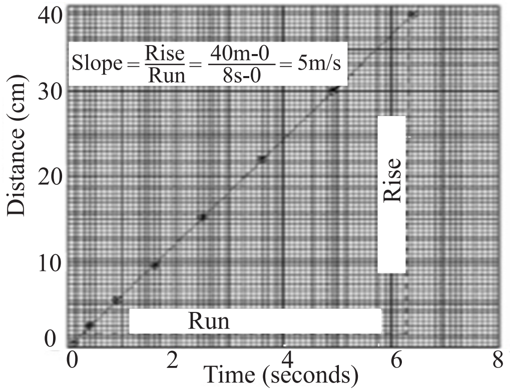


Figure 4.

(i) Position-time graph

You have learnt that the position, x, of an object, undergoing a uniform motion at any time, t, is given by $x = x_0 + vt$. To draw the position –time graph, put position on the y-axis, and time on the x-axis, as shown in Figure 5(a). As you can see, the graph forms a straight line, known as a linear graph, and its slope will give velocity, as shown in Figure 5(b).

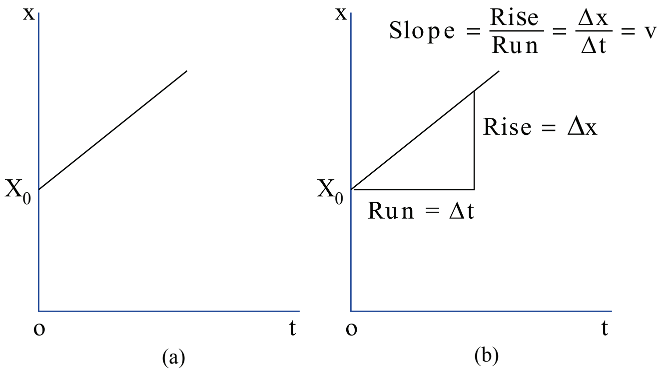


Figure 5. Position-time graph of uniform motion

Next, let us see some properties of position-time graph.

- If the graph is flat or horizontal, then the object is not moving, the slope is zero, and hence the velocity is zero, as shown in Figure 5.
- When the graph slopes upwards less steeply, then the velocity is low.
- We should point out that if the slope is positive, then the velocity is positive. If the slope is negative and the graph goes down, then the velocity is negative relative to a reference point.

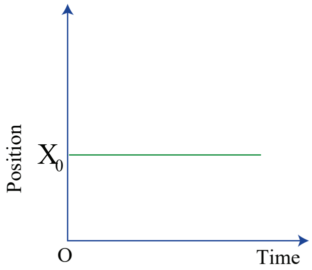


Figure 6.

(ii) Displacement-time (x-t) graphs

A displacement–time graph helps to determine instantaneous velocity at any time in a given time interval. Methods of drawing displacement vs time graph is the same as that of position vs time graph, except the later passes through the origin, and the equation becomes $d = x - x_0$, or $d = vt$. The displacement-time graph becomes, as shown in Figure 7.

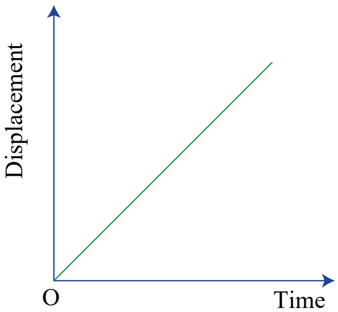


Figure 7. The s-t graph of uniform motion

(iii) Velocity-time graph

The velocity- time graph of a uniform motion is a horizontal straight line, as shown in Figure 8(a). In this case, the slope of the graph is zero. Zero slope means, the velocity is not changing, or the object is not accelerating.

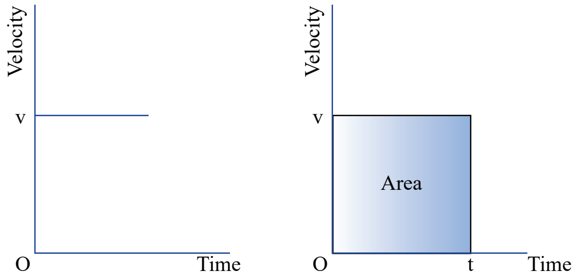


Figure 8. (a): Velocity-time graph, (b) The area under v-t curve gives displacement

The shape of the area under this graph is a simple rectangle, as shown in Figure 8(b). The result of this area gives displacement.

$$\Delta x = \text{Area} = \text{velocity x time}$$

If we review our kinematic equation, we quickly realize that the area under the curve is actually the displacement. This general rule holds even when the velocity is not constant.

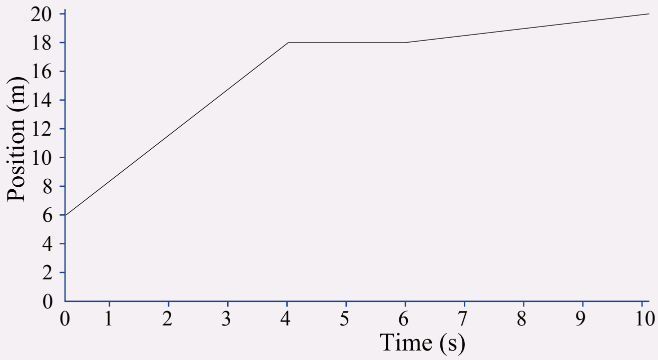
Examples

The position-time graph, shown below, represents motion of an object along a straight line.

(a) Interpret the graph from 0 to 10 seconds.

(b) Determine the velocity of the motion for each segment.

(c) What is the total displacement? What is the average velocity?



Solution:

(a) The motion started at x_0 = 6m. Since the line segment is a straight line sloping upwards, the motion between 0 and 4 s is a uniform motion. The object stays at rest between 4s and 6s. Finally, the object traveled with a uniform velocity in the time interval between 6s and 10s.

(b) The velocity under each segment is determined by calculating the slope,

$$v_1 = \text{slope}_1 = \frac{18m - 6m}{4s - 0s} = 3m/s$$

$$v_2 = \text{slope}_2 = \frac{18m - 18m}{6s - 4s} = 0$$

$$v_3 = \text{slope}_3 = \frac{20m - 18m}{10s - 6s} = 0.5m/s$$

(c) The total displacement is

$\Delta x = x - x0 = 20m - 6m = 14m$

The average velocity, v, is, is then

$$v = \frac{\Delta x}{t} = \frac{14m}{10s} = 1.4m/s$$

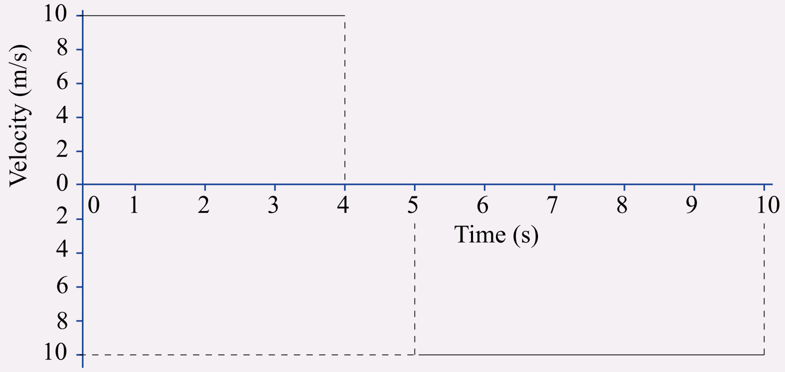
Examples

Consider the velocity-time graph, shown below. If the initial position is zero (x0 = 0),

(a) Determine the total distance.

(b) What is the total displacement?

(c) Draw the position-time graph.



Solution: $v_1 = 10$ m/s, $v_2 = 0$, $v_3 = -10$ m/s

(a) First, we will calculate the distance moved in each segment. Then, the sum of these gives the total distance.

$$s_1 = |v_1|\Delta t_1 = 10m/s \times (4s - 0) = 40m$$

$$s_2 = |v_2|\Delta t_2 = 0 \times (5s - 4s) = 0$$

$$s_3 = |v_3|\Delta t_3 = 10m/s \times (10s - 5s) = 50m$$

The total distance, s, is then

$$s = s_1 + s_2 + s_3 = 40m + 0 + 50m$$

$$s = 90m$$

(b) In the same way as above, we first calculate the displacement moved in each segment. Then, the sum of these gives the total displacement.

$$\Delta x_1 = v_1 \Delta t_1 = 10m/s \times (4s - 0) = 40m$$

$$\Delta x_2 = v_2 \Delta t_2 = 0 \times (5s - 4s) = 0$$

$$\Delta x_3 = v_3 \Delta t_3 = -10m/s \times (10s - 5s) = -50m$$

The total displacement, Δx, is then

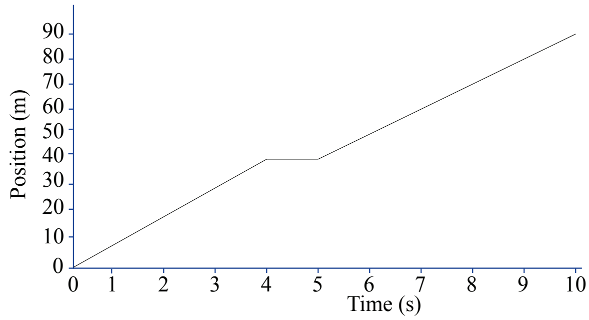
$$\Delta x = \Delta x_1 + \Delta x_2 + \Delta x_3 = 40m + 0 - 50m$$

$$\Delta x = -10m$$

This result shows that, although the motion is started from the origin towards the positive x-direction, its final destination becomes to be 10 m to the left of the origin.

(c) To draw the displacement – time graph, first we develop the table using values at turning points only, then we can draw the graph by connecting these points only as shown below.

Time in s	Position in m
0	0
4	40
5	40
10	90

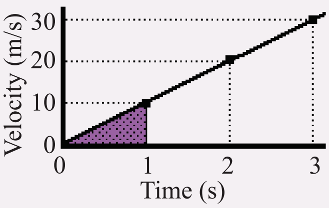


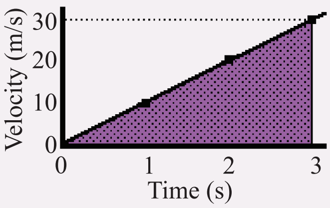
Examples

Determine the displacement of the object:

(a) during the first second, and

(b) during the first 3 seconds from the velocity-time graph shown below





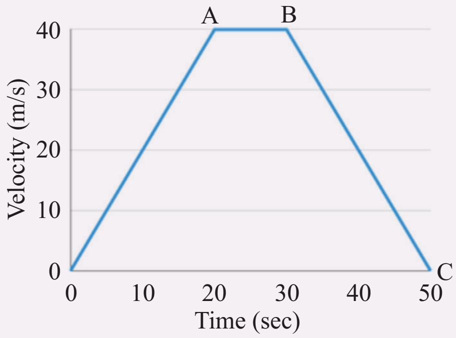
Solution

Displacement of the object during 1st second = shaded area of triangle in 1st figure of velocity time graph = ½ ×10 m/s × 1s = 5 m.

Displacement of the object during first 3 second = ½ × 30 m/s × 3s = 45 m.

Examples

A bus driver travelling from Sinkor to Broad Street starts from rest and accelerates uniformly to a speed of 40 m/s after 20 seconds. He maintains a steady speed for 10 seconds and then decelerates uniformly to bring the bus to rest after a further 20 seconds. Calculate the acceleration, retardation, and total distance covered.



Solution

For first 20 second acceleration $= \dfrac{\text{change in velocity}}{\text{time interval}} = \dfrac{(40\text{ m/s} - 0)}{(20\text{ s} - 0)} = 2\text{ ms}^{-2}$

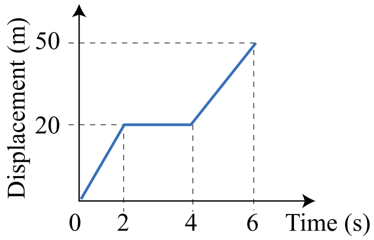
from B to C there will be retardation $= \dfrac{\text{change in velocity}}{\text{time interval}} = \dfrac{(0 - 40\text{ m/s})}{(50\text{ s} - 30\text{ s})} = -\dfrac{40}{20} = -2\text{ms}^{-2}$

total distance covered = area of trapezium of velocity time graph

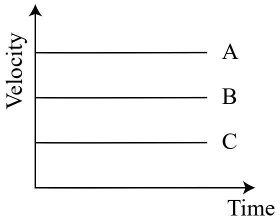
$$= \frac{1}{2}(50\text{ m/s} + 10\text{ m/s}) \times 40\text{ s} = \frac{1}{2} \times 60\text{ m/s} \times 40\text{ s} = 1200\text{ m}$$

Exercises

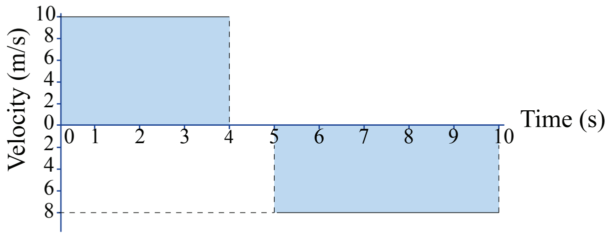
1. The figure at the right shows the displacement vs time graph of a certain motion.
   (a) Determine the slope of each segment.
   (b) In which time interval is the motion the fastest?
   (c) What is the speed between 2 s and 4s?
   (d) What is the average speed of the entire motion?
   (e) Draw the speed vs time graph.



2. The velocity-time graphs in the figure below indicate speeds of three people in a local race? If all start from the same position and at the same time, which person will win the race?



3. The velocity – time graph, shown below, represents motion along a straight line.
   (a) What does the total area of the shaded region represent?
   (b) What is the total displacement of the motion?
   (c) What is the total distance?
   (d) Draw the displacement-time and distance-time graphs.



4. The velocity of a car increase from 20 m/s to 30 m/s in 1 minute.
   (a) Draw the displacement vs time graph.
   (b) Draw the velocity vs time graph.
   (c) Calculate the area under velocity vs time graph.
   (d) Draw the acceleration -time graph and calculate the area under the a-t curve.

B. Freely falling bodies (gravity)

A free falling object is an object that is falling under the sole influence of gravity. Any object that is being acted upon only by the force of gravity is said to be in a state of free fall. There are two important assumptions that are true of free-falling objects:

- Air resistance on a free-falling object is neglected.

All free-falling objects, near earth's surface, accelerate downwards at a rate of 9.8 m/s^2; usually denoted by "g" and is called the acceleration due to earth's gravity.

If you release a ball freely from a certain height, you will observe the ball speeding up. If an object travels downward and speeds up, then its acceleration is downward.

There was story about Galileo Galilei (1564–1642), an Italian scientist. According to the story, he climbed up a leaning tower of Pisa to test out his theory of free fall. He dropped two cannon balls, one large one, and the other small one. The destructive thought of everyone watching was that the larger one, would hit the ground first as it has more mass. However, they both hit the ground at the same time. Galileo had realized that all objects, dropped near Earth, accelerate at the same rate g = 9.8m/s/s and it is only air resistance that slows them down.

You may observe that if a stone and a piece of paper are released freely from the same height and at the same time, it is obvious that the stone will hit the ground first. However, this is due to air resistance having a greater effect on the piece of paper. If you do this experiment in vacuum, both will fall at the same time.

In 1971, an American astronaut David Scott dropped a hammer and a feather simultaneously freely from the same height to demonstrate free fall. The hammer and the feather both fell exactly at the same rate and so hit moon's surface at the same time. This is because; there is no atmosphere and so no air resistance on the Moon.

Free fall is a uniformly accelerated motion. We can then use the equations of uniform acceleration to relate displacement, acceleration, velocity and time at any time up to just before impact.

Examples

Suppose a feather is dropped freely from the top of a 20 m high building.

(a) How long would it take for the feather to hit the ground?

(b) What would be the velocity of the feather at the instant it strikes the ground? (Take $g = 10\ m/s^2$)

Solution:

$v_0 = 0$, $g = 10\ m/s^2$, $h = 20\ m$

In this case, h is used to denote the displacement, to mean height.

(a) The time taken for the whole flight of the feather is calculated from equation Since $v_o = 0$, we have

$s = v_o t + 1/2\ gt^2$.

$h = 1/2\ (gt^2)$

After some rearrangements, we find

$$t = \sqrt{\frac{2h}{g}} = \sqrt{\frac{2 \times 20m}{10m/s^2}} = 2s$$

(b) The final velocity, $v = gt = 10m/s^2 \times 2s = 20m/s$, or,

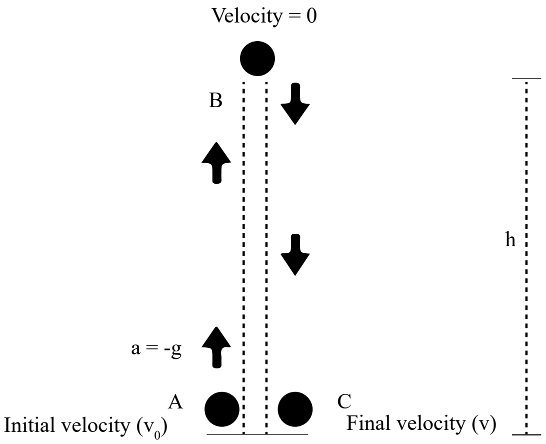
$$v = \sqrt{v_0^2 + 2gh} = \sqrt{2gh}$$

$$v = \sqrt{2 \times 10m/s^2 \times 20m} = 20m/s$$

Vertical upward motion

When a ball is thrown vertically upwards from the ground, its velocity reduces gradually under the influence of earth's gravity working towards the opposite direction of the ball's motion. So, the ball is moving with retardation until it attains the maximum height where the velocity becomes zero.

Then, ball starts falling uniformly downwards and velocity increases gradually under the influence of gravity reaching back to its projection plane.



(i) For maximum height during upward motion from A to B

$$(0)^2 = (v_0)^2 + 2(-g)h$$

$$h = (v_0)^2/2g$$

(ii) For time taken to reach maximum height

$$0 = v_0 + (-g)t$$

$$t = v_0/g$$

(iii) Total time of flight (T)

$$T = 2t$$

$$T = 2(v_0/g)$$

Examples

A tennis ball is thrown vertically upward at an initial velocity of 5 m/s. Find the maximum height it can reach and how long will it take for the ball to reach the maximum height? ($g = 10\ ms^{-2}$)

Solution

Maximum height reached by tennis ball, $h = (v_0)^2/2g$

$= (5\ m/s)^2 / 2 \times 10\ m/s^2$

$= 1.25\ m$

Time taking by the ball to reach maximum height $t = v_0/g$

$= (5\ m/s)\ /\ 10\ m/s^2$

$= 0.5\ s$

Activity 1

Demonstrate motion of freely falling bodies due to gravity

The set up of the activity is shown in the Figure. Equipment needed are clamp (right angle), base and support rod, free fall adapter; balls (13 mm and 19 mm) and meter stick (or metric tape measure).

The purpose of this activity is measuring the acceleration due to gravity in the absence of any external force except gravity.

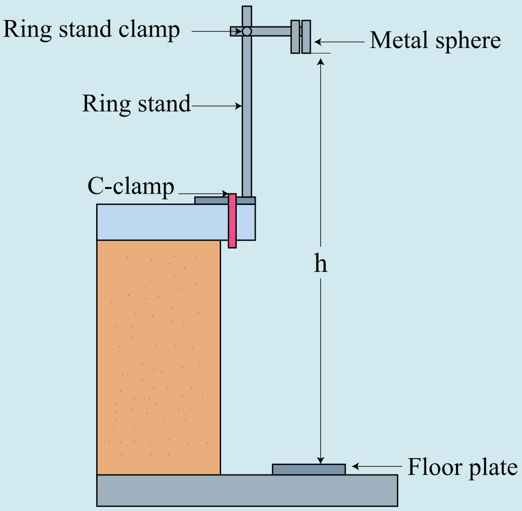
Theory:

An equation describing the motion of a body under the action of gravity and starting from rest, given as

$$h = \frac{1}{2}gt^2$$

The method is to meaure the time to fall through the given distance for difference masses and calculate "g" for each trial using the formula given by

$$g = \frac{2h}{t^2}$$



Questions:

- What are sources of error?

Expected results:

1. Objects of different masses will fall with the same acceleration.
2. The acceleration due to gravity is approximately equal to 9.8 m/s/s.

Exercises

1. What is free fall?
2. Does the acceleration due to gravity the same as $g = 9.8\ m/s^2$ everywhere in the universe?
3. Why does a stone fall faster than a feather when they are released freely at a certain height?
4. A ball, released freely from the top of a building, strikes the ground after 20 seconds.
   (a) What is the velocity of the ball at the instant it strikes the ground?
   (b) How tall is the building? $g = 9.80\ m.s^{-2}$

2.5 Newton's Laws of Motion and Newton's Law of Universal Gravitation

Upon completion of this topic you will be able to:

- use the Newton's laws of motion and analyze the effect of gravity on falling bodies; and
- discuss the force of gravitation between objects.

In this section, learners will start from Newton's laws of motion. The three laws of motion help you understand how objects behave when standing still, when moving and when forces act upon them.

Newton had developed another outstanding theory, known as Newton's law of universal gravitation. Newton's law of universal gravitation is about the universality of gravity. Newton's place in the Gravity Hall of Fame is not due to his discovery of gravity, but rather due to his discovery that gravitation is universal. ALL objects attract each other with a force of gravitational attraction. Gravity is universal. This topic describes Sir Newton's three laws and the law of universal gravitation as well.

KEY TERMS

- Inertia, the resistance of mass to changes in its of motion

Newton's Laws of Motion

Newton's laws of motion are the three basic laws of classical mechanics that describe the relationship between the motion of an object and the forces acting on it. These laws are treated below.

(i) Newton's First Law of Motion

Newton's first law of motion explains what would happen to the state of motion of a body in the absence of any external force. This law states:

- An object at rest will remain at rest or of travelling at a constant velocity unless acted upon by an unbalanced external force.

Newton's first law of motion implies that things cannot start, stop, or change direction all by themselves, and it requires some force from the outside to cause such a change. Constant velocity in the definition implies that an object moving around a curve or in a circle must have force acting on it. Newton's first law means a force is always required to make an object:

- speed up
- slow down
- or change direction.

If an object is not doing any of these, then the object is either stationary or moving with constant speed to a specific direction.

Mass and inertia

From Newton's first law, we can notice that objects have the property of resist change in state of motion. Objects tend to "keep on doing what they're doing."

It is the natural tendency of objects to resist changes in their state of motion. This tendency to resist changes in their state of motion is described as inertia. In this case, Newton's first law of motion is also known as the law of inertia.

Inertia is the property of an object to remain at rest or move at a steady speed in a straight line.

You may have experienced inertia in different situations. If you are running and want to stop suddenly or change direction of your motion abruptly, there is a property that pushes you in the direction of you initial direction. When you are in a bus, you lean backward when the bus starts to move and you lean forward when the bus tries to stop. These phenomena show how your mass resists change in state of motion.

The inertia of a body depends on its mass. The greater the mass of the body, the greater its inertia will be. This is why it is easier to throw a small object than a heavy object, since the heavy object has bigger mass and hence bigger inertia than the smaller one. Thus, mass is a measure of inertia.

(ii) Newton's Second Law of Motion

Newton's second law of motion describes what would happen to a body if it experiences an unbalanced force. This law relates the unbalanced force acting on the body, the mass of the object and the resulting acceleration. Newton's second law states:

- The acceleration of an object is directly proportional to the magnitude of the net force, in the same direction as the net force, and inversely proportional to the mass of the object.

The mathematical form of Newton's second can be defined as follows:

$$F = ma$$

where F is the unbalanced force, m is mass of the object and a is the acceleration.

The SI unit of acceleration is m/s/s, and that of mass is kg. Therefore, the SI unit of force is newton (N), where 1 N = 1 kgm/s^2.

Weight

Weight is defined as the force of gravity on objects. The force with which the earth pulls an object of mass, m, located on its surface, is given by

$$W = mg$$

where g is the acceleration due to gravity.

Examples

A man of mass 62 kg rides a bike of total mass of 63 kg. If he brakes and reduces its velocity from 10 m/s to 0 m/s in 2 seconds, determine the magnitude of the braking force.

Solution: m = 62 kg + 63 kg = 125 kg, t = 2s, v = 10 m/s, v_0= 0

The acceleration of the bike is

$$a = \frac{v - v_0}{t} = \frac{0 - 10m/s}{2s} = -5m/s^2$$

The net force acting on the sum of masses of the man and the bike is

F = ma = 125 kg × (-5 m/s^2) = - 625 N

The negative sign indicates that the force is retarding force. In other words, the force is acting opposite to the initial direction of motion.

Activity 2

Demonstrating Newton's first and second laws using Pendulum Pairs

A pendulum is anything that can hang and swing back and forth. A swing set on a playground is a pendulum. For this activity, pendulums will put force on a string that is stretched between two objects. Start with a single pendulum, and then explore what happens if two equal pendulums are on the same string.

Materials

Chairs or stools (2)

- String or yarn piece, approx. 30" long (1)
- String or yarn pieces, approx. 10" long (2-3)
- Two identical items that can be tied to the string and swing (empty bottles, washers, pens, small toys, etc.)

Stop watch

Procedures ahead of time:

1. Cut string into correct lengths
2. Tie each end of the 30" string to the chairs or stools at the same height
3. Tie a short string to each of the items you found. Make sure that each string is the same length
4. Tie the loose end of one of the short strings onto the middle of the longer string
5. Make sure that the pendulum can swing without hitting anything. Tie the string shorter if you need to.

Procedure:

Set up a simple pendulum, and test it. Add a second equal pendulum and find out what happens when only one of the pendulums starts swinging. Try different ways of releasing the pendulums.

1. Attach one end of a short string to one of the items you have. Tie the other end of the short string to the middle of the long string.
2. Gently pull back on the pendulum to lift if a little bit, and let it go. Observe what happens as the pendulum swings. Think about what might happen if a second pendulum were added to the device.
3. Attach a second pendulum to the long horizontal string.
4. Try to put the pendulums at a sufficient distance away from each other so that they do not hit one another. Raise the first pendulum and let it swing. How did your prediction compare to what you observed?
5. Try a different way of making the pendulums move. What happens if both pendulums are pulled and released at the same time in the same direction? What happens if both pendulums are pulled opposite directions and released at the same time? Try it and record what you observe on a chart like the one below.

Action on pendulums	Observation on pendulum 1	Observation on pendulum 2	Remark
Released in the same direction at the same time			

Action on pendulums	Observation on pendulum 1	Observation on pendulum 2	Remark
Released in the opposite direction at the same time			

What might happen if the two strings aren't the same length? What might happen if one pendulum is heavier than the other? Make your predictions and test them out.

Note:

As a pendulum attached to a string swings, it pushes and pulls on the string. The force of the pendulum pulling on the string is transferred to the second pendulum. Lightly hold the long string between two fingers while the pendulums swing to feel these forces.

(iii) Newton's Third Law of Motion

Newton's third law states:

- For every action force there is an equal and opposite reaction force.

When two bodies interact, they apply forces on each other that are equal in magnitude and opposite in direction. Therefore, a single force cannot exist; forces are always in pairs: action-reaction force pairs. Action-reaction force pairs do not cancel each other since they act on two different objects.

A variety of action-reaction force pairs are evident in nature. Few of such pairs are listed as follows:

- When a fish pushes the water backwards with its pins, the water pushes the fish forward with a force of equal magnitude. This helps the fish to propel forward.
- The wings of the bird should push the air downwards in order to fly upward.
- A helicopter lifts upward by pushing the air downwards.
- When a hammer hits a nail, the nail exerts a force of on the hammer. The two exchange forces of exactly equal magnitudes in the opposite directions.
- To move forwards, you push the floor backwards. At the same time, the floor exerts a force on you. So, when you walk, it is the floor that pushes you along!
- When the bowstring pushes the arrow, then the arrow pushes the bowstring forwards.

When you jump, you push the Earth downward. According to Newton's Third Law, the "Earth will also push you upward," and this is the force that causes you to accelerate into the air. Why doesn't the Earth appear to accelerate? According to Newton's Second Law of motion, the acceleration of an object depends on two things:

- the net force on the object, and
- the object's mass (inertia).

Examples

The force that the earth exerts on an object of mass m is $F_O = mg$, which is the weight of the object. Compare acceleration of the two objects.

Solution: Assume the object-earth system is isolated. According to Newton's third law, the object should also pull the earth upward with equal amount of force given by $F_E = m_E a_E$, where aE is the acceleration of the earth. Since action-reaction force pairs are equal in magnitude and opposite in direction, then

$$m_E a_E = -m_O g$$

From this, we can derive the acceleration of the earth as

$$a_E = -\left(\frac{m_O}{m_E}\right)g$$

Then if the mass of the object is 6 kg and assume g = 10 m/s^2, then the acceleration of the Earth,

$$a_E = -\left(\frac{6\text{kg}}{6 \times 10^{24}\text{ kg}}\right) \times 10\text{m/s}^2 = -10^{-23}\text{m/s}^2$$

The negative sign indicates that the direction of earth's acceleration is opposite to that of the object. When the object accelerates downward at 10m/s^2, the Earth accelerates at 10^{-23}m/s^2 upwards. Even this acceleration is canceled out by other forces by other objects. You can see how the difference in mass affects acceleration. The earth accelerates almost none.

Activity 3

Demonstrating Newton's third law of motion by hammering a nail

When a hammer is forced a nail into wood, the speed, v, of the hammer at the instant it hits the head is directly proportional to the depth, d, it moves into the wood, The force can be represented by a mass falling vertically onto the nail, as shown in the figure (b). Then, we have the equation

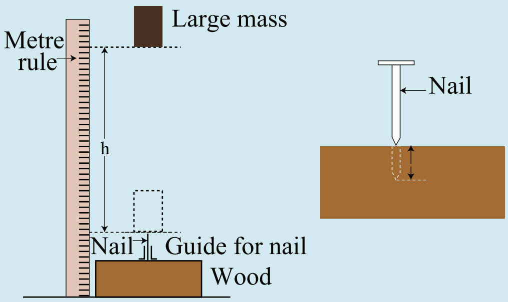
$$d = kv^n$$

where k and n are constants.

Next you design an activity to investigate the relationship between v and d so as to determine a value for n.

In this activity, you will:

- vary v and measure d for each value of v.
- keep the mass to be dropped as well as the wood constant.



Procedure:

1. Build the experimental setup, as shown in figure (a).
2. Measure h with a meter rule and drop the mass freely from height h. The mass will fall, hit and force the nail into the wood to depth d.
3. Determine the velocity v of the mass at the instant it hits the nail using the equation:

$$v = \sqrt{2gh}$$

4. Measure the depth d with vernier calipers. Repeat this and take the average value of d.
5. Change the height of the falling mass to vary v. Repeat this for different values.

6. Taking the logarithm of $d = kv^n$, we obtain
   $\log d = n\log v + \log k$
7. Plot $\ln d$ against $\ln v$ graph. From the graph, the slope is n and the y-intercept is ln k.
   Expected result
   If the graph is a straight-line, then the suggested relationship is correct.
8. Finally, the desired value (the value of n) is determined by finding the slope of the graph, as:

$$n = \frac{\log d}{\log v}$$

Safety Precaution:

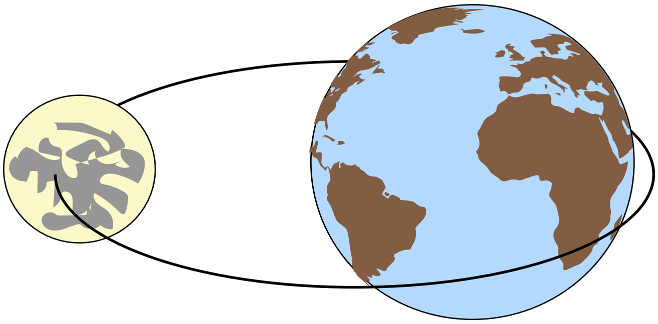
- Prevent yourself from injury of the falling mass.
- Use of microscope when measuring d.
- Avoid parallax error while reading.

Expected results:

- logd vs logv graph is a stright line

Newton's Law of Universal Gravitation

According to Newton, if there were no force acting on it, moon would not move on a curved path, instead it would travel on a straight path. Based on such observations of the path of the Moon, Newton proposed a formula to describe how this force must behave. In doing so, he imagined that the laws of nature that applied to objects on Earth also applied to heavenly bodies. The law has since been confirmed by experiments carried out between a pair of masses on Earth, and is known as Newton's universal law of gravitation.



If two masses m_1 and m_2 are a distance r apart, Newton claimed that the gravitational force F between these objects is directly proportional to the product of their masses and is inversely proportional to the square of the distance that separates their centers. The magnitude of the force between the two objects is, then given by

$$F = \frac{Gm_1m_2}{r^2}$$

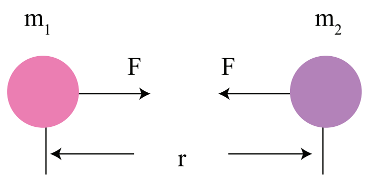


Figure 9. Gravitational force of attraction between two objects

where the proportionality constant G represents the universal gravitational constant ($G = 6.67 \times 10^{-11}\ Nm^2/kg^2$).

Activity 4

Demonstrating universal gravitational law

Objective:

Determine the universal gravitational constant (G).

Procedure:

Determine g using the experiment you performed above.

The weight of an object of mass m, located on Earth's surface is

$$w = mg, \text{ or } F_G = \frac{GM_Em}{R_E^2}$$

- where and $w = F_G$ is radius of the Earth or distance between the centers of the object and the Earth.

$$w = F_G$$

- Equating these two equations, canceling out "m" at all sides and going through some steps, you will obtain

$$G = \frac{gR_E^2}{M}$$

Examples

A sack of half quintal barley is placed on equator.

(a) What is the force of gravitational attraction between the earth ($m_E = 5.98 \times 10^{24}$ kg) and the barley? Compare this value for F = mg.

(b) What would be the force if the barley were taken to a height equal to the radius of the earth above Earth's surface? (Take radius of the Earth to be 6.38×10^6 m.)

Solution: $m_E = 5.98 \times 10^{24}$ kg, $r_E = 6.38 \times 106$ m, mb = 50 kg

(a) The solution of the problem involves substituting known values into the universal gravitation equation and solving for F. Thus,

$$F = \frac{Gm_E m_b}{r_E^2} = \frac{(6.67 \times 10^{-11} Nm^2/kg^2)(5.98 \times 10^{24} kg)(50kg)}{(6.38 \times 10^6 m)^2}$$

$$F = 486.7N$$

Weight on Earth's surface,

$F = m_b g = 50 \text{ kg} \times 9.8 \text{ m/s}^2 = 490 \text{ N}$

(b) If the barley were taken to a height of rE above Earth's surface, the force becomes

$$F = \frac{Gm_E m_b}{(2r_E)^2} = \frac{(6.67 \times 10^{-11} Nm^2/kg^2)(5.98 \times 10^{24} kg)(50kg)}{(2 \times 6.38 \times 10^6 m)^2}$$

$$F = 121.68N$$

Observe that the force of gravity decreases as distance increases. Distance of separation is much more influential when a significant variation is made.

Satellite

A satellite is a body which is revolving continuously in an orbit around a much larger body. There are two types of satellites which is Natural and Artificial.

Natural satellites are those which are made by nature. For example, earth is satellite of sun and moon is a satellite of earth. With the advancement of science and technology, many man-made satellites have been put in different orbits around the earth. Such satellites are called as artificial satellites. First artificial satellite was launched by Russia named Sputnik 1 in year 1957.

Geo-stationary satellite

A geo-stationary satellite is an earth-orbiting satellite place at an altitude of approximately 36,000 km directly over the equator that revolves in the same direction in which the earth rotates (west to east). At this altitude, one orbit takes 24 hours, which is the same length of time that the earth requires to rotate once on its on axis. The term geo-stationary comes from the fact that such a satellite appears nearly stationary in the sky as seen by a ground-based observer.

Escape Velocity

The minimum velocity with which a body has to be projected vertically upwards from the surface of the earth or from any other planet so that it just crosses the gravitational field of earth or that planet and never return on its surface is called escape velocity.

Escape velocity on earth (v_e) = $\sqrt{2GM/R}$ or $\sqrt{2gR}$;

Where R = radius off earth = 6400 km

M = mass of earth = 6×10^{24} kg

G = gravitational constant = $\mathbf{6.67408 \times 10^{-11}\ N\ m^2\ kg^{-2}}$

g = acceleration due to gravity = 9.8 ms^{-2}

For earth's surface, escape velocity is approximately 11.2 km/s.

Exercises

1. What is inertia? How do you measure it? Which has smaller inertia; bicycle or train?
2. Imagine a rock is thrown to a certain direction where there exists neither friction nor gravity. If it is intially moving at 10 m/s, what is its velocity after long time? What keeps it to move?
3. A 2-kg object is moving horizontally with a speed of 4 m/s. How much net force is required to keep the object moving at this speed and in this direction?
4. Suppose the acceleration due to gravity on earth's surface is 10m/s^2. If a 100 N force is applied to lift a 190 kg object, does it accelerate upwards?
5. A 15 kg object is acted on by a force of 600 N. What will be the acceleration of the object?
6. When you are standing still, is the net force acting on you equal to zero? Can you remain still while forces are acting on you?
7. A 4 N ball needs to be accelerating in the vertical direction at 10 m/s^2 to reach its target height. How much force must be exerted in the vertical direction to accomplish this?
8. Do action and reaction force pairs cancel out each other?
9. What happens according to Newton if you let an untied balloon go?
10. By what factor does the gravitational attraction force between two objects change if their separation distance is reduced by half?
11. The planet Jupiter is about 300 times more massive than Earth. A 500-N person on Earth weighs about 1500 N on the surface of Jupiter, but not 150000 N. Why?
12. Are ocean tides results of the Moon's gravity acting on Earth?

Summary

- M Motion is the phenomenon in which an object changes its position over time with respect to a fixed reference position, known as frame of reference.

- Motion is mathematically described in terms of position, displacement, distance, velocity, acceleration, speed, and time.
  - The position of an object refers to where it is at any particular time relative to a convenient frame of reference. A frame of reference is an observation point where motions of an object are described.
  - The reference frame may be at rest or moving at a constant rate with respect to the earth.
- Distance is a measure of "the path length of a journey an object has covered during its motion". Distance is a scaler and its SI unit is m.
- Displacement is the measure of "how far an object is out of its initial position." It is a vector with SI unit m.
- If the initial position of an object x0, then the object's displacement when it is at position x,

$$d = \Delta x = x - x_0$$

- The speed of an object tells how slowly or how fast the object is moving. Speed is a scalar, and its SI unit is meter, m.
- Average speed, v, is defined as the total distance traveled, S, divide by the total time, t, taken:

$$v = \frac{s}{t}$$

- The SI unit of speed is meters per second (m/s). Other non-SI units of speed are kilometers per hour (km/h), miles per hour (mph), etc.
- Speed at a specific instant in time is called instantaneous speed. A car›s speedometer reads its instantaneous speed.
- Velocity can be defined as the rate of change of position with respect to a frame of reference. Thus, average velocity, $\vec{v}$, is defined as

$$\vec{v} = \frac{\Delta\vec{x}}{\Delta t}$$

- Velocity is a vector quantity. The SI unit of velocity is meter per second (ms-1), which is the same as that of speed.
- Uniform motion is defined as the motion of an object in which the object travels with a constant speed along a straight line. We say the object is moving with a constant speed if it covers equal distances in equal intervals of time, irrespective of the duration of the time.
- The average velocity of an object, undertaking a uniform motion, is the same as its instantaneous velocity at any time.

- If an object starts from an initial position x_0 and travels at a constant speed v, then its position at any time t is given by

  $$x = x_0 + vt$$

- And the displacement at any time t, becomes

  $$d = x - x_0 = vt$$

- The acceleration of an object is defined as the rate of change of its velocity, The average acceleration, $\vec{a}_{av}$, is given as

  $$\vec{a}_{av} = \frac{\Delta\vec{v}}{\Delta t}$$

- The SI unit of acceleration is meter per second per second (m/s/s or $1m/s^2$).
- If the velocity of an object, moving along a straight line, changes equally in equal intervals of time, then the acceleration is constant and usually called uniform acceleration.
- Equations describing a uniformly accelerated motion when $t_0 = 0$ and initial velocity v_0, then acceleration (a), velocity (v) and displacement (s) at any time (t) are:

  $$a = \frac{v - v_0}{t}$$

  $$v = v_0 + at$$

  $$v_{av} = \frac{v_0 + v}{2}$$, where Vav is the average velocity

- $$s = v_0 t + \frac{1}{2}at^2$$

  $$v^2 = v_0^2 + 2as$$

- A freely falling object is an object that is falling under the sole influence of gravity.
- When an object is undergoing free fall it will accelerate downwards at,

  $g = 9.8m/s^2$, downwards

- Newton's first law (The law of inerta) states that a body at rest continue to be at rest or a body in uniform motion will continue in uniform motion unless a net external force acts on it. This property of bodies to resist changes in their state of motion is called inertia.
- Newton's second law states that the acceleration of an object is directly proportional to the magnitude of the net force, in the same direction

as the net force, and inversely proportional to the mass of the object. Mathematically,

$$F = ma$$

- Newton's third law states that for every action force there is an equal and opposite reaction force. According to this law, a single force cannot exist; forces are always in pairs: action-reaction force pairs.
- Newton discovered that ALL objects attract each other with a force of gravitational attraction. Gravity is universal. This force of gravitational attraction is directly proportional to the masses of both objects and inversely proportional to the square of the distance that separates their centers.

$$F = \frac{Gm_1m_2}{r^2}$$

- where G is the universal gravitational constant ($G = 6.67 \times 10^{-11}\ Nm^2/kg^2$).

Exercises

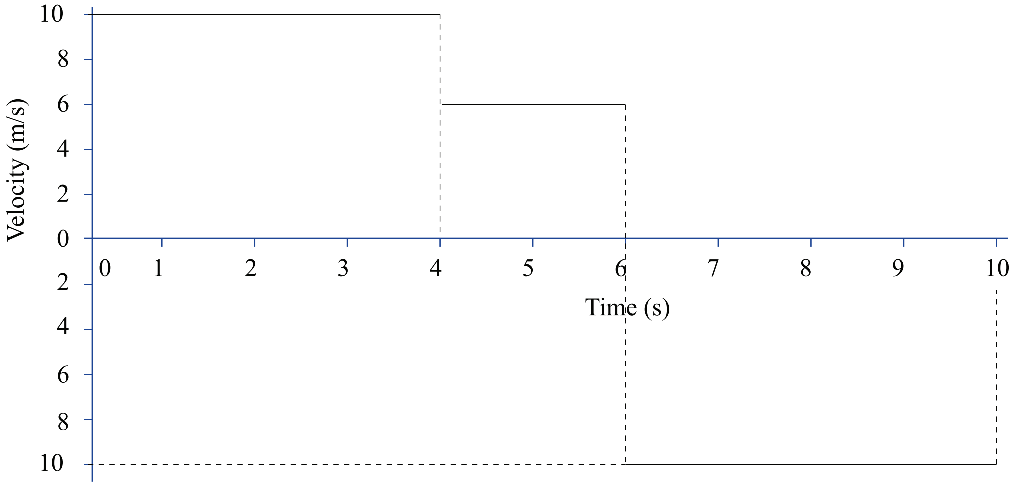
1. EA cyclist rides from position $x_0 = 2$ km to $x = 5$ km. what is the displacement of the cyclist?
2. A cat, initially at $x = 6$m, runs in the positive x-direction and catches a rat after running a displacement of 4m. if it returned back on the same path and ate it at $x = -10$m,
   (a) What is the total distance?
   (b) What is the total displacement?
3. When do both distance and displacement of an object be equal?
4. An aircraft cruises with an average speed of 300 m/s. how long does it take for the aircraft to cover a total distance of 1000 km?
5. A car travels at a constant speed of 20 km/h for 4 hours and then at 50km/h for 3 hours. What was the average speed of the car?
6. A student walks from an initial position of 100m to a final position of 10m for 30 seconds. What was the velocity of the student?
7. A woman was driving a car with a uniform velocity of 10m/s for 70 seconds in the positive x-direction. If the final position is 80m, what was the initial position?
8. What does 6 m/s2 mean?
9. A taxi increases its velocity from 30 m/s to 50m/s in 10 seconds. A lorry driver drives at a uniform velocity of 60 m/s for 10 seconds.
   (a) Which car has bigger acceleration?
   (b) Which car is faster?

10. A goat starts to accelerate from rest at 5 m/s^2 at the instant it sees a leopard. The leopard catches the goat in 2 seconds. How far did the goat run before it is caught by the leopard?

11. A train, initially moving at 80 m/s, reduces its speed uniformly at a rate of 1 m/s^2.
    (a) How far did it travel before it comes to rest?
    (b) How long did it travel before it comes to rest?

12. What does the slope of the position-time graph represent?

13. he graph in the figure shown represents velocity vs time graphs.



    (a) Determine the total distance traveled.
    (b) What is the total displacement?
    (c) Draw the displacement-time graph.

14. A ball is released freely from the top of a 25 m tall building.
    (a) What would be the velocity of the ball at the instant it strikes the ground?
    (b) Draw the displacement vs time graph.
    (c) Draw the velocity vs time graph.
    (d) Draw the acceleration vs time graph and calculate the area under the a-t curve.

15. How much unbalanced force is required to produce an acceleration of 6 m/s^2 on a 20 kg object?

16. A constant unbalanced force of 500 N brings a 50 kg object to rest in 20 seconds. What was the initial velocity of the object?

17. The gravitational force between two objects is 10 N. what would be the force if their separation doubles?

18. If the pull of the earth on moon is the action force, what will be the reaction force?
19. A 10 kg and a 100 kg objects are released freely above the earth at the same time and at the same place.
    (a) Which object has greater acceleration?
    (b) Which object has greater weight?
    (c) Which object falls first?

P10CH03

CHAPTER 3

WORK, ENERGY AND POWER

Chapter Contents

Chapter Outcomes

Learners will be able to:

- Appreciate the works of machines in life and the interrelationship between
  - matter and energy;
  - work and energy;
  - work/energy and Power do simple calculations on Work, Energy and Power.

Introduction

Work and energy are important concepts in physics as well as in our day to day life. Everyday we spend a lot of time and effort doing things such as walking, writing, climbing stairs, reading books. In its everyday sense, the term work means to do something that takes physical or mental effort. But in physics, work has a distinctly different meaning. In this unit we study the concepts of work and the related concepts of kinetic energy, potential energy, and power. In addition, we will use the principle of conservation of mechanical energy to solve a variety of problems.

Key Terms

- Potential energy is the ability to do work due to its position or shape.
- Kinetic energy is the ability of an object to do work due to its motion.

Upon completion of this topic students will be able to:

- identify the characteristics of work, energy and power and their S.I units;
- solve simple problems involving work, energy(potential and kinetic) and power
- distinguish between work input and work output
- compute potential and kinetic energies problems.
- demonstrate the law of conservation of mechanical energy and its application.

Pushing a big table or pulling a heavy desk in a classroom requires considerable effort. The greater the force you exert, the greater the effort. The greater the distance you move the object, the greater the effort. If you push or pull long and hard enough, your exertions can even make you tired. These observations are the basis for our definition of work.

Force in the direction of displacement

In the simplest case, work is done when a force is applied to an object and the object moves in the direction of the applied force. In a situation like this, work, W, is defined as force times the distance moved.

$$\text{Work} = \text{Force} \times \text{distance}$$

$$W = F \times s$$

In the SI system, work has a unit of newtons times meters (N.m), or joules (J). That is, 1 J = 1 N.m.

This is the simple case where the force is in the same direction as the displacement as shown in Figure 1.

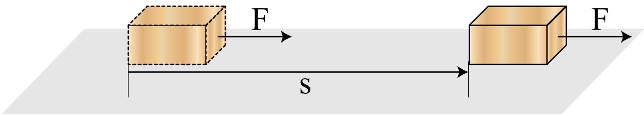


Figure 1.

As shown in Figure 1, a constant force, $\vec{F}$, pushes a box through a displacement, $\vec{s}$. In this special case the force and displacement are in the same direction, and the work done on the box by the force is W = Fs.

Examples

You push your desk 1.20 m along the floor with a horizontal force of 10 N. How much work does this force do on the desk?

Solution:

s = 1.20 m W =?

F = 10 N

Using the definition of work, we get

W = F.s = 10 N × 1.20 m

W = 12 N.m = 12 J

Examples

A factory worker pushes a 25 kg loaded cart a distance of 6 m along a level floor by pushing horizontally to it. In this time, he does 450 J of work. Calculate the force the worker applied.

Solution:

s = 6 m F =?

W = 450 J

From the definition of work, we solve for the force, F

W = Fs

$$F = \frac{W}{s} = \frac{450\text{ J}}{6\text{ m}} = \frac{450\text{ N.m}}{6\text{ m}}$$

F = 75 N

Examples

By how much will a body be displaced if 60 J of work is done by applying a force of 5 N on it?

Solution:

W = 60 J   s =?

F = 5 N

From the definition of work, we solve for the distance s

$$s = \frac{W}{F} = \frac{60\ J}{5\ N} = \frac{60\ N.m}{5\ N} = 12\ m$$

Discuss 1:

In what ways is the word "work" as used in everyday language the same as defined in physics? In what ways is it different? Give examples of both.

Examples

A weight lifter lifts a 350 N weight from ground level to a position over his head, a vertical distance of 2 m. How much work does the weight lifter do, assuming he moves the weight at constant speed?

Solution:

The weight lifter exerts a force equal to, at least the weight, 350 N. Thus,

F = 350 N, up in the direction of the displacement

s = 2 m

The work done by the lifter is the

$W = F.s = 350\ N \times 2\ m = 700\ J$

Note: This is the work done against gravity. In order to lift an object vertically up, we have to overcome the force of gravity on the weight. In other words, we have to apply a force F equal to the weight (mg) of the object and lift it at a constant speed through a height h.

Examples

1. A 20 J of work is done in order to raise a bag through a height of 1 m. What is the mass of the bag? (Use $g = 10\ m/s^2$)

Solution:

W = 20 J   m =?

h = 1 m

From the equation W = Fs = (mg)h, we solve for the mass m

$$m = \frac{W}{gh} = \frac{20\ J}{10\ m/s^2 \times 1\ m} = \frac{20\ N.m}{10\ m/s^2 \times 1\ m}$$

m = 2 kg

Exercises

How large is one joule?

Explanation:

One joule is nearly the work done in lifting an apple from your waist to the top of your head.

Note: $1\ J = 1\ N.m = 1\ (kg.m/s^2).m = 1\ kg.m^2/s^2$

Investigate

The joule is named for the British physicist James Prescott Joule (1818–1889). Joule made major contributions to the understanding of energy, heat, and electricity. Search for joule's major contributions to the science world and discuss how it is helping this generation.

Exercises

To get out of bed in the morning, do you have to do work? Explain.

Explanation

Yes, you must do work against the force of gravity to raise your body upward out of bed

Force at an angle to the displacement

Imagine pulling a box along a horizontal ground. If the force you exert is horizontal, all of your effort moves the box. If your force is at an angle, only the horizontal component of your applied force causes a displacement and contributes to the work. If the angle between the force and the direction of the displacement is θ, as in Figure 2, work can be expressed as follows:

$$W = (F \cos\theta)s$$

$$W = Fs \cos\theta$$

Remember that work is a scalar quantity. It can, however, be positive, zero, or negative, depending on the value of the angle θ.

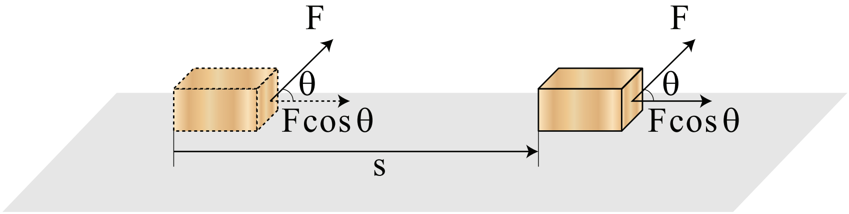


Figure 2.

Note:

(i) Work is positive if the force has a component in the direction of motion (i.e., $0 < \theta < 90^o$).

(ii) Work is zero if the force has no component in the direction of motion (i.e., $\theta = 90^o$).

(iii) Work is negative if the force has a component opposite to the direction of motion (i.e., $90^o < \theta < 180^o$).

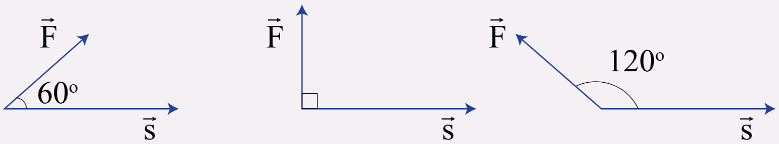
Examples

1. For each case shown in the figure below, determine the work done by the force F = 60 N, if the displacement s = 4 m?

Solution:

F = 60 N W =?

s = 4 m



(a) For the first case, $\theta = 60^o$. The work done by the force F is

$$W = Fs\cos 60^o = (60\text{ N})(4\text{ m})(0.5) = 120\text{ J}$$

(b) For the second case, $\theta = 90^o$. The work done by the force F is

$$W = Fs\cos 90^o = (60\text{ N})(4\text{ m})(0) = 0\text{ J}$$

(c) For the third case, $\theta = 60^o$. The work done by the force F is

$$W = Fs\cos 120^o = (60\text{ N})(4\text{ m})(-0.5) = -120\text{ J}$$

Exercises

Each of the boxes shown in Figure 4 moves through the same horizontal distance, s. The force applied to each of the boxes has the same magnitude, F. Notice, however, that the direction of the force is different in each of the cases A, B, C, and D. In which case is the work done (a) positive, (b) negative, and (c) zero?

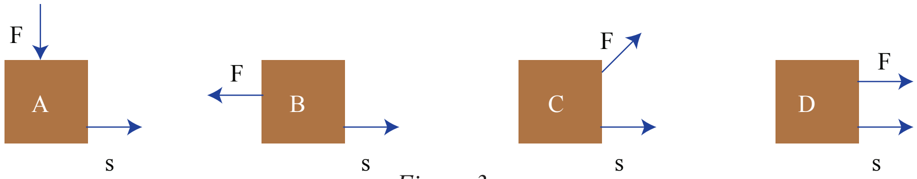


Figure 3.

Energy

Now that we understand the concept of work, we can use it to define energy. Anything which is capable of doing work is said to possess energy. A falling water has energy because it can do work by turning the turbine of a generator. A battery has energy because it can rotate an electric motor that does work. Wind has energy because it can turn the blades of wind turbines. From these examples, we can define energy as follows:

- **Energy is the ability to do work.**

Energy comes in diffrent forms. Mechanical energy, electrical energy, chemical energy, nuclear energy, and light energy are some of the forms of energy. In this lesson, however, we shall study only mechanical energy, which consists of two distinct types: (i) kinetic energy (KE), associated with the motion of an object; and (ii) potential energy (PE), associated with the position of an object relative to the ground or some other bodies taken as a reference.

Kinetic Energy (KE) is the ability of an object to do work because of its motion. As shown in Figure 5, the moving hammer can do work on the nail driving it into the wall because it has kinetic energy. If an object of mass m moves with a velocity v, its kinetic energy is given by:

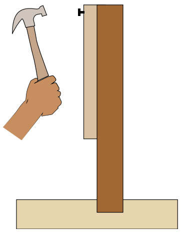


Figure 4.

$$KE = \frac{1}{2}mv^2$$

Examples

An athlete of mass 58 kg runs at a speed of 8 m/s. what is her kinetic energy?

Solution:

m = 58 kg   KE =?

v = 8 m/s

The kinetic energy of the athlete is

$$KE = \frac{1}{2}mv^2 = \frac{1}{2} \times 58\ kg \times (8\ m/s)^2 = \frac{1}{2} \times 58\ kg \times 64\ m^2/s^2$$

KE = 1856 J

Examples

A 1800 kg car is moving at a speed of 5.0 m/s. (a) What is its kinetic energy? (b) What is the car's kinetic energy if its speed is doubled to 10 m/s?

Solution:

m = 1800 kg   (a) KE =?

v = 5.0 m/s   (b) KE =? if v = 2 × 5 m/s = 10 m/s

(a) The kinetic energy of the car when the speed is 5 m/s is

$$KE = \frac{1}{2}mv^2 = \frac{1}{2}(1800\ kg)(5\ m/s)^2 = 22{,}500\ J$$

(b) Kinetic energy depends on the speed squared. Therefore, doubling the speed quadruples the kinetic energy.

$$KE = \frac{1}{2}mv^2 = \frac{1}{2}(1800\ kg)(10\ m/s)^2 = 90{,}000\ J$$

or KE = 4(22,500 J) = 90,000 J

Examples

A 7.00 kg bowling ball moves at 3.00 m/s. How fast must a 2.50 g table-tennis ball move in order to have the same kinetic energy as the bowling ball? Is this speed reasonable for a table-tennis ball in play?

Solution:

Bowling ball: m_b = 7 kg   Tennis ball: m_t = 2.50 g

v_b=3 m/s v_t =?

First, calculate the kinetic energy of the bowling ball

$$KE_b = \frac{1}{2}mv^2 = \frac{1}{2}(7\text{ kg})(3\text{ m/s})^2 = 31.5\text{ J}$$

Then, solve for the speed of the table-tennis ball having the same kinetic energy as the bowling ball.

$$KE_t = KE_b$$

$$\frac{1}{2}m_t v_t^2 = 31.5\text{ J}$$

$$v_t = \sqrt{\frac{2(31.5\text{ J})}{2.5 \times 10^{-3}\text{ kg}}} = \sqrt{\frac{63\text{ J}}{2.5 \times 10^{-3}\text{ kg}}} = \sqrt{25{,}200\text{ m}^2/\text{s}^2}$$

$$v_t = 158.75\text{ m/s}$$

Notice that this speed would be very fast for a table-tennis ball.

Discuss: 2

Two bullets have masses of 3 g and 6 g, respectively. Both are fired with a speed of 40 m/s. Which bullet has more kinetic energy? What is the ratio of their kinetic energies?

Examples

What is the speed of an 8.0×10^4 kg airliner with a kinetic energy of 1.0×10^9 J?

Solution:

$m = 8.0 \times 10^4$ kg $v = ?$

$KE = 1.0 \times 10^9$ J

Solving the kinetic energy equation for v, we get

$$v = \sqrt{\frac{2KE}{m}} = \sqrt{\frac{2 \times 1.0 \times 10^9\text{ J}}{8.0 \times 10^4\text{ kg}}} = \sqrt{25{,}000\text{ m}^2/\text{s}^2}$$

$$v = 158\text{ m/s}$$

Relationship between work and kinetic energy

There is a very simple connection between work and the change in kinetic energy. Specifically, the total work done on an object equals the change in its kinetic energy. This connection is known as the work-energy theorem:

Work-Energy Theorem:

total work = change in kinetic energy

$$W_{total} = \Delta KE$$

$$W_{total} = KE_f - KE_i$$

Thus, the work–energy theorem says that when a force acts on an object over a distance—doing work on it—the result is a change in the speed of the object, and hence a change in its kinetic energy.

Note:

Doing positive work on an object increases the kinetic energy of the object. When negative work is done on an object, its kinetic energy decreases.

Examples

How much total work is required to accelerate a 1000 kg car from 20 m/s to 30 m/s (Figure 6).

Solution

$m = 1000$ kg $\quad v_i = 20$ m/s

$v_f = 30$ m/s

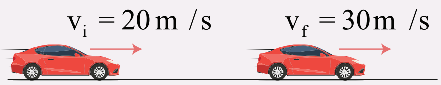


Figure 5.

Using the work-energy theorem, we get

$$W_{total} = KE_f - KE_i = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$$

$$W_{total} = \frac{1}{2}(1000\text{ kg})(30\text{ m/s})^2 - \frac{1}{2}(1000\text{ kg})(20\text{ m/s})^2$$

$$W_{total} = 2.5 \times 105\text{ J}$$

Discuss 3

(i) Can kinetic energy ever be negative?

(ii) (a) If the kinetic energy of a baseball is doubled, by what factor has its speed increased? (b) If its speed is doubled, by what factor does its kinetic energy increase?

Examples

A car accelerates from rest to 36 km/h. Later, on a highway it accelerates from 36 km/h to 72 km/h. Which takes more energy, going from 0 to 36, or from 36 to 72?

Solution:

1^{st} – from 0 km/h to 36 km/h: $v_i = 0$

$v_f = 36 \times (10/36)$ m/s = 10 m/s

$$W_{total} = KE_f - KE_i = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$$

$$W_{total} = \frac{1}{2}m(10\ m/s)^2 - \frac{1}{2}m(0) = (50m)\ J$$

2^{nd} – from 36 km/h to 72 km/h: $v_i = 10$ m/s

$v_f = 72$ km/h $= 72 \times (10/36) = 20$ m/s

$$W_{total} = \frac{1}{2}m(20\ m/s)^2 - \frac{1}{2}m(10\ m/s)^2 = (150m)\ J$$

Without knowing the mass of the car, it is possible to see that it takes more work (energy) in the 2^{nd} case.

Potential Energy The potential energy of an object is its ability to do work because of its position or shape. For example, when we wind a clock, the work done by us stored energy in the spring and the spring runs the clock by unwinding itself. The spring possesses potential energy because of its deformed condition (shape).

The most common form of potential energy is the gravitational potential energy (GPE). In raising a body of mass m to a vertical height h from the surface of the earth, work is done against the force of attraction of the earth. The amount of work done is stored as potential energy in the body. Thus, due to its position at a higher level, the body possesses more capacity to do work than it had when it was at ground level. The gravitational potential energy (or simply potential energy, PE) is given by the equation:

$$PE = mgh$$

where h is the height above a given reference point.

Figure 7 illustrates that lifting a ball onto a shelf requires a certain amount of work. The ball can remain on the shelf for any length of time, but if the ball falls back to the floor (Figure 7 (b)), gravity does the same work on the ball that you did to lift it in the first place. Thus, the work done in lifting the ball is stored as potential energy, ready for conversion to kinetic energy when the ball falls.

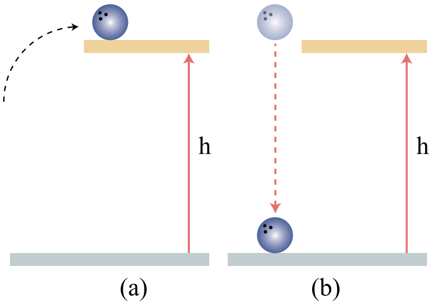


Figure 6.

Examples

A 300 g book rests on a table top 80 cm above the floor. What is the potential energy of the book with respect to the floor? (Use $g = 9.8\ m/s^2$)

Solution:

$m = 300\ g = 0.3\ kg$ PE =?

$h = 80cm = 0.8\ m$

From the definition of potential energy,

$PE = mgh = 0.3\ kg \times 9.8\ m/s^2 \times 0.8\ m$

$PE = 2.35\ J$

Examples

A bag of mass 2.5 kg is resting on a chair 0.5 m high. What will be the increase in the potential energy when the bag is placed on a table top 0.90 m high? (Use $g = 10\ m/s^2$)

Solution

$m = 2.5\ kg$ $h_2 = 0.90\ m$

$h_1 = 0.5\ m$ $\Delta PE =?$

Initially the bag was on the chair, at a height of 0.5m above the floor. Its PE with respect to the floor is:

$PE = mgh$

$PE = 2.5\ kg \times 10\ m/s^2 \times 0.5\ m = 12.5\ J$

When the bag is placed on the table top 0.90 m high, its PE with respect to the floor is

$PE = mgh = 2.5\ kg \times 10\ m/s^2 \times 0.9\ m$

$PE = 22.5\ J$

The increase in PE as the bag is taken from the chair where its PE is 12.5 J to the table top where its PE is 22.5 J is:

Increase in PE = 22.5 J – 12.5 J = 10 J

or $\Delta PE = 10\ J$

Examples

40 J of work is done in order to raise an object through a vertical height of 10 m. What is the mass of the body?

Solution:

$W = 40\ J$ and $h = 10\ m$

The work done to raise the object equals the energy transferred to the body. This energy is, PE = mgh. Therefore,

$$W = mgh$$

$$40\ J = m \times 10\ m/s^2 \times 10\ m$$

$$m = \frac{40\ J}{100\ m^2/s^2} = 0.40\ kg$$

Examples

A 4 kg block is lifted to a height of 0.5 m above a tabletop (Figure 8). Find its potential energy (a) relative to the tabletop, (b) relative to the floor. (Use $g = 9.8\ m/s^2$)

Solution:

(a) Relative to the tabletop, h = 0.5 m

$PE = mgh = 4\ kg \times 9.8\ m/s^2 \times 0.5\ m$

$PE = 19.6 J$

(b) But the tabletop itself is 1 m above the floor. The block's height above the floor is 1.5 m, and so its potential energy relative to the floor is

$PE = mgh = 4\ kg \times 9.8\ m/s^2 \times 1.5\ m$

$PE = 58.8\ J$

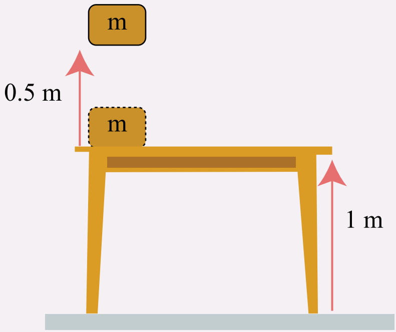


Figure 7.

Notice that gravitational potential energy depends on the position of the object above the ground (or any reference point).

Discuss 4:

Four identical balls are shown in Figure 9. Which ball has the largest potenial energy relatve to the ground? Which ball has the smallest potential energy? Why?

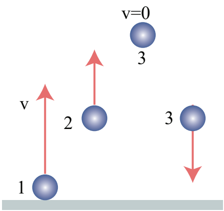


Figure 8.

Conservation and transformation of energy

Energy can never be created or destroyed — it can only be transformed from one form to another. For example, electric energy is converted to heat energy in an electric stove, to light energy in an electric bulb. On burning kerosene, chemical energy of the oil changes into heat energy. When you rub your palms together vigorously, they get heated. Mechanical energy is converted into heat energy.

When energy in one form disappears, it appears in another form and the total energy remains the same. This is the principle of conservation of energy. It is stated as follows:

- **Energy can neither be created nor destroyed, but it can only be transformed from one form into another and can be transferred from one object to another.**

Conservation of mechanical energy The sum of the potential and kinetic energies of an object is referred to as its mechanical energy, ME.

Mechanical energy = potential energy + kinetic energy

$$ME = PE + KE$$

If friction effects are neglected, energy is transformed from potential energy to kinetic energy and vice versa, but the sum of the two is constant. Thus, mechanical energy is conserved when friction is absent.

Examples

A stone is released from rest from the top of a building 45 m high. Using conservation of mechanical energy, find the speed of the stone when it reached the ground. (Use $g = 10\ m/s^2$)

Solution:

$v_{top} = 0$ $\qquad v_{bottom} = ?$

$h = 45\ m$

Applying the conservation of mechanical energy, we get

$$ME_{top} = ME_{bottom}$$

$$(KE + PE)_{top} = (KE + PE)_{bottom}$$

At the top, $v = 0$. Thus, $KE_{top} = 0$. At the bottom (ground), $h = 0$. Thus, $PE = 0$.

$$(\tfrac{1}{2}mv^2 + mgh)_{top} = (\tfrac{1}{2}mv^2 + mgh)_{bottom}$$

$$0 + mgh = \tfrac{1}{2}mv^2 + 0$$

$$mgh = \tfrac{1}{2}mv^2$$

$$v^2 = 2gh$$

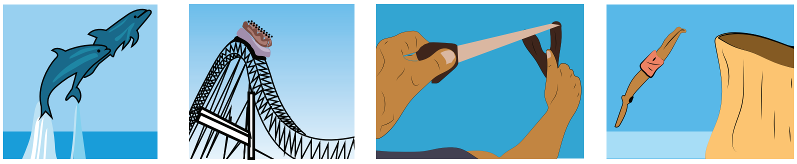
$$v = \sqrt{2gh} = \sqrt{2 \times 10\ m/s^2 \times 45\ m} = \sqrt{900\ m^2/s^2}$$

$$v = 30\ m/s$$

Note: Conservation of energy simplifies many physics problems.

Figure 10 shows real world examples of energy conservation.

(a) This dolphin has lots of kinetic energy as it leaves the water. At its highest point its energy is mostly potential energy



a b c d

Figure 9.

(b) Gravitational potential energy is stored energy associated with an object's height above the ground. As this coaster ascends, energy is stored as gravitational potential energy. As it descends, this stored energy is converted into kinetic energy.

(c) The boy does work by stretching the rubber band to give it potential energy.

(d) The diver is speeding up as gravitational potential energy is transformed into kinetic energy.

Examples

At a swimming pool, a girl slides down a water slide. She starts at a height of 6.0 m and ends at a height of 1.0 m above the water level with a short horizontal segment (Figure 11). What is her speed at the bottom of the slide?

Solution

$h = 6.0$ m

$g = 10$ m/s^2

Applying the conservation of mechanical energy, we have

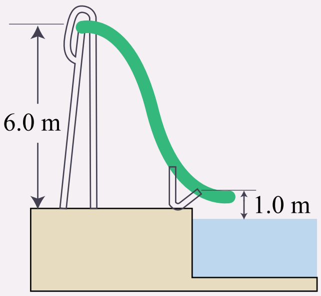


Figure 10.

$$\begin{pmatrix}\text{ME at the top}\\ \text{of the slide}\end{pmatrix} = \begin{pmatrix}\text{ME at the bottom}\\ \text{of the slide}\end{pmatrix}$$

$$(KE + PE)_{top} = (KE + PE)_{bottom}$$

$$(\tfrac{1}{2} mv^2 + mgh)_{top} = (\tfrac{1}{2} mv^2 + mgh)_{bottom}$$

At the top, v = 0 and at the bottom h = 0 (reference level). Thus,

$$0 + (mgh)_{top} = \tfrac{1}{2} mv^2 + 0$$

$$v^2 = 2gh$$

$$v = \sqrt{2gh} = \sqrt{2 \times 10\ \text{m/s}^2 \times 6\ \text{m}} = \sqrt{120\ \text{m}^2/\text{s}^2}$$

$$v = 11\ \text{m/s}$$

Examples

The motion of a pendulum is a good example of the conversion of gravitational potential energy into kinetic energy and back again. A child on a swing is pulled up as shown in Figure 11. At point A, the child has gravitational potential energy because of her height above the rest (bottom) position of the swing. When released, the child swings downward and the potential energy is converted into kinetic energy. At the lowest point, position B, the child has only kinetic energy, which equals the original potential energy. The child then swings upward to the other side, point C, and converts the kinetic energy to potential energy. If h = 80 cm, find the speed of the child at B, bottom (or lowest point) of the swing.

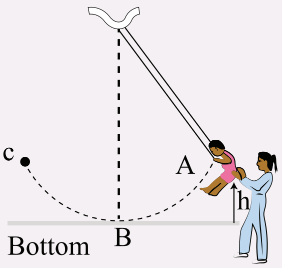


Figure 11.

Solution

$h = 80\ \text{cm} = 0.80\ \text{m}$

Applying the conservation of mechanical energy, we get

$ME_A = ME_B$

$PE_A = KE_B$

$mgh = \frac{1}{2} mv^2$

$v = \sqrt{2gh} = \sqrt{2 \times 10\ \text{m/s}^2 \times 0.80\ \text{m}}$

$v = 4\ \text{m/s}$

Examples

A smooth slope is inclined to the horizontal. A block of mass 4 kg is released from rest at the top of the slope and reaches the bottom with a speed of 7 m/s (Figure 12). Find (a) the potential energy at the top of the slope (b) the height h of the slope.

Solution

(a) We use the conservation of energy to find the PE at the top.

$PE_{top} = KE_{bottom}$

$PE_{top} = \frac{1}{2} mv^2$

$PE_{top} = \frac{1}{2} \times 4\ \text{kg} \times (7\ \text{m/s})^2$

$PE_{top} = 98\ \text{J}$

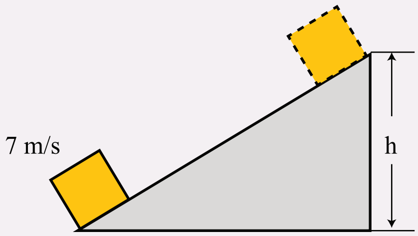


Figure 12.

(b) The height h is

$PE_{top} = KE_{bottom}$

$$mgh = \frac{1}{2} mv^2$$

$$h = \frac{v^2}{2g} = \frac{(7\ m/s)^2}{2 \times 10\ m/s^2} = \frac{49\ m^2/s^2}{20\ m/s^2}$$

$$h = 2.45\ m$$

Power

Power is the rate at which work is done, or the rate of transfer of energy. The faster a machine can do work, the most powerful it is.

$$\text{Power} = \frac{\text{Work done}}{\text{time taken}}$$

$$P = \frac{W}{t}$$

The SI unit of power is joule per second (J/s). This unit is given a name watt (W).

$$1\ W = 1\ J/s$$

Since watt is a small unit, we use the kilowatt (kW) and the megawatt (MW).

$$1kW = 1000\ W = 10^3\ W$$

$$1\ MW = 1000000\ W = 10^6\ W$$

There was another unit of power called the horse power (hp). 1 hp = 746 Watt

Examples

What is the power that can be developed by a man having a mass of 70 kg when he runs up a flight of stairs to the height of 10 m in 20 s? ($g = 10\ m/s^2$)

Solution:

$m = 70\ kg$ $t = 20\ s$

$h = 10\ m$ $P = ?$

When the man goes up the stairs, the energy transferred is:

$$PE = mgh = 70\ kg \times 10\ m/s^2 \times 10\ m = 7\ 000\ J$$

The power developed by the man is then

$$p = \frac{W}{t} = \frac{7000\ J}{20\ s} = 350\ W$$

Examples

Two different machines are used to do the same work. The work needed in both cases in 1500 kJ. One does this work in 100 s, and the other does it in 250 s. Which one is more powerful?

Solution:

W = 1500 kJ

For machine 1: t = 100 s, and P_1 = 1500 kJ/100 s = 15 kJ/s = 15 kW

For machine 2: t = 250 s, and p_2 = 1500 kJ/250 s = 6 kJ/s = 6 kW

Therefore, machine 1 is more powerful than machine 2.

Examples

(a) How many joules of energy does a 100-watt lightbulb use every hour? (b) How fast would a 60 kg person have to run to have that amount of kinetic energy? Is it possible for a person to run that fast?

Solution

P =100 W (a) W =?

t = 1 hour = 60 × 60 = 3600 s (b) v =? (for m = 60 kg)

(a) Using the definition of power, we solve for the energy (work)

W = p × t = 100 W × 3600 s = 360,000 J

(b) From the work-energy theorem, we have

$$W = \Delta KE = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2 = \frac{1}{2}mv_f^2 - 0$$

$$v_f^2 = \frac{2W}{m}$$

$$v_f = \sqrt{\frac{2W}{m}} = \sqrt{\frac{2 \times 360{,}000\ J}{60\ kg}} = \sqrt{12{,}000\ m^2/s^2}$$

v_f = 109.5 m/s

No it is not possible.

Discuss 5

Figure 13 shows a 0.40 kg block sliding from A to B along a frictionless surface. The kinetic energy of the block at A is 37 J. What is the kinetic energy of the block when it reaches B?

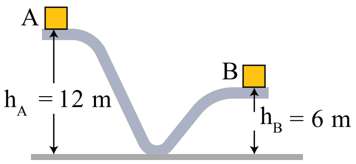


Figure 13.

Exercises

Engine 1 does twice the work of engine 2. Is it correct to conclude that engine 1 produces twice as much power as engine 2? Explain.

Explanation:

In this problem, Engine 1 does twice the work of Engine 2. We are asked if the given information is enough to conclude that engine 1 produces twice as much power as engine 2.

The answer is no. The definition of power states that power is the rate in which work is done. We are not given the time in which the work is done, so we cannot compare the power the engines produce.

Power depends on force and speed

Let's see how power is related to force and speed. Consider a car moving uphill with a constant speed v. As the car travels a distance s, the work done by the engine is W = Fs, and the power it delivers is

$$p = \frac{W}{t} = \frac{Fs}{t} = F\left(\frac{s}{t}\right)$$

Since the car has a constant speed, v = s/t, it follows that

$$p = Fv$$

For example, suppose you push a heavy box with a given force. You produce twice as much power when you push at 2 m/s than when you push at 1 m/s. Similarly, if you push a box at a given speed, you produce twice as much power if your force is 40 N rather than 20 N. The connection between power, force, and speed is very straightforward.

Examples

It takes a force of 1500 N to keep a 1200 kg car moving with constant speed. If the engine delivers 50 hp to the drive wheels, what is the maximum speed of the car?

Solution:

F = 1500 N	$p = 50\text{ hp} = 50 \times 746 = 3.73 \times 10^4$ W
m = 1200 kg	v =?

From the equation p = Fv, we solve for v:

$v = p/F = 3.73 \times 10^4 \text{ W}/1500 \text{ N} = 25$ m/s

Upon completion of this topic students will be able to:

- distinguish between the different types of simple machines
- describe the advantages of using these machines

Everyone uses some machines every day, some are simple tools, such as bottle opener and screwdrivers; others are complex, such as washing machines, sewing machines, bicycles, and automobiles. Machines, whether powered by engines or people, make tasks easier. A machine does work easily by changing either the magnitude or the direction of a force as it transmits energy to the task. In this unit you will investigate how machines make doing work easier.

Key Terms

- Mechanical advantage
- Velocity ratio
- Work output
- Work input
- Load
- Effort
- Efficency

Types of Simple Machines

All machines are constructed from these simple machines: lever, pulley, inclined plane, wedge, screw, and wheel and axle (Figure 14).

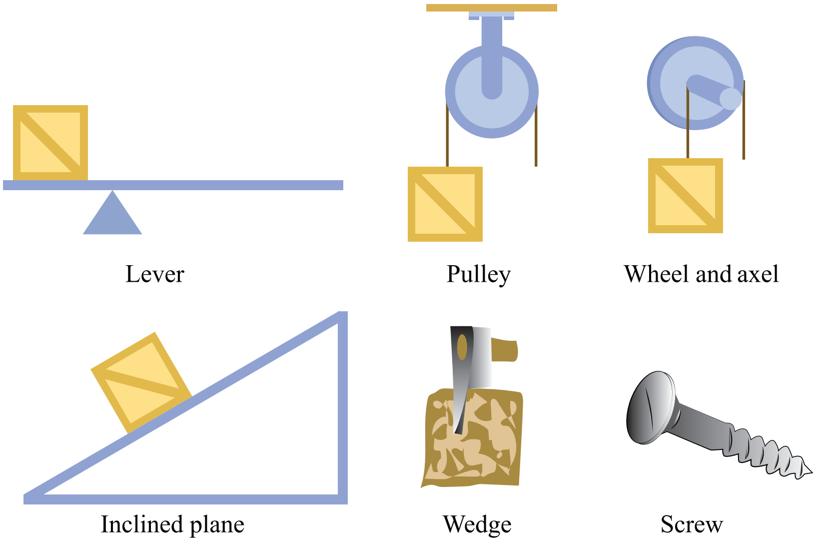


Figure 14.

A machine is a device that is used to transfer energy from one object to another and allow work to be done easily. Consider the bottle opener shown in Figure 16. When we use the opener, we lift the handle, thereby doing work on the opener. The opener lifts the cap, doing work on it. The work we do is called the input work, W_{in}. The work the machine does is called the output work, W_{out}.

Work, as you recall, is the transfer of energy by mechanical means. We put work into a machine, in this case, the bottle opener. That is, we transfer energy to the opener. The opener, in turn, does work on the cap, transferring energy to it. The opener is not a source of energy, so the cap cannot receive more energy than you put into the opener. Thus, the output work can never be greater than the input work. The machine simply helps in the transfer of energy from us to the bottle cap.

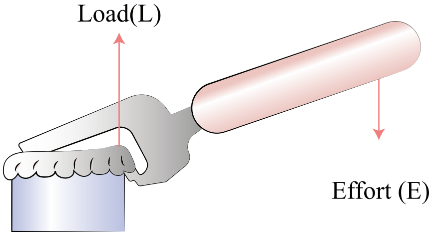


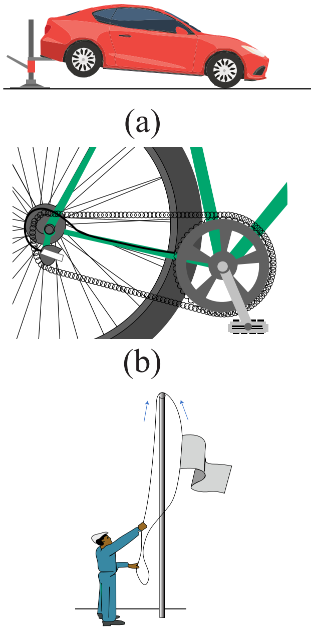
Figure 15.

Advantages of machines

We use a machine for one of the following purposes.

1. Machines can be used to multiply force. For example, a car jack (lever) can be used to lift a much heavier weight of the car (Figure 16 (a)).
2. Machines can be used to multiply speed. The gears of a bicycle (wheel-and-axle) shown in Figure 16 (b) propel the rider much faster than he or she could go without aid from the machine. Note, however, that a single simple machine may be used to multiply force or speed, but not both.
3. Machines can be used only to change direction. When we used a single fixed pulley on a flag pole to raise a flag (Figure 16(c)), the only advantage we get is the change in direction. (We pull the rope down, and the flag goes up.)

In every machine we are concerned with two forces,namely, load and effort.


(a)
(b)
(c)
Figure 16.

Effort Force (E) is the force applied to the machine. This is the input force exerted on the machine.

Load (L) s the force applied by the machine on the object (or weight) to be raised or moved. This is the output (resistance) force exerted by the machine.

For example, in Figure 17 (a), a person applies a force of 60 N on the jack handle to produce a lifting force of 1200 N on the car. Therefore, the effort force (or input force) is 60 N and the load (or resistance force) is 1200 N.

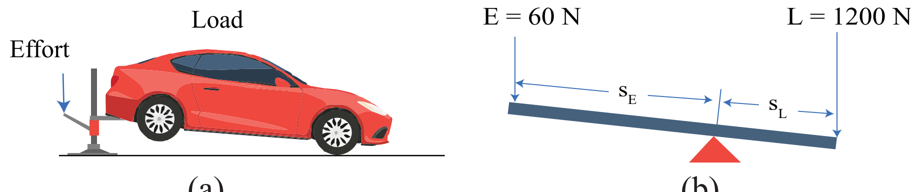


Figure 17.

When the effort force is applied it moves a certain distance, s_E (effort distance). At the same time the load moves a distance s_L (load distance). In Figure 17 (b), we see that a smaller force (E) applied to a longer distance (s_E) can raise a large weight (L) but only by a small distance (s_L).

Mechanical advantage

We use a simple machine to make a task easier or to enable to do something that we could not do without it. The number of times a machine multiplies the effort force is the mechanical advantage (MA) of the machine. To calculate mechanical advantage, we divide the load by the effort force.

$$MA = \frac{\text{Load}}{\text{Effort}} = \frac{L}{E}$$

Mechanical advantage (MA) has no units.

This is the actual mechanical advantage of machines. Many machines, such as the bottle opener and the car jack, have a mechanical advantage greater than one. When the MA is greater than one, the machine increases the force applied. Such machines are force multipliers.

Examples

What is the mechanical advantage (MA) of the jack shown in Figure 18 (a)?

Solution

Load, L = 1200 N (This is the resistance or output force)

Effort, E = 60 N (This is the input force)

Using the definition of mechanical advantage, we get

$$MA = \frac{L}{E} = \frac{1200\ N}{60\ N} = 20$$

Notice that this machine multiples the input force 20 times.

Examples

The mechanical advantage of a pair of pliers is 6. A force of 36 N is exerted on the handle. What force is exerted on a wire in the plier?

Solution

MA = 6 L =?

E = 36 N

From the definition of MA = L/E, we solve for the load.

$L = E \times MA = 36\ N \times 6 = 216\ N$

Velocity ratio (VR) Is the ratio of the distance the effort moves to the distance the load moves.

$$VR = \frac{\text{Distance the effort moves}}{\text{Distance the load moves}}$$

$$VR = \frac{s_E}{s_L}$$

Note that you measure distances moved to calculate the velocity ratio, VR, but you measure the forces exerted to find the actual mechanical advantage, MA.

Velocity ratio is also known as ideal mechanical advantage (IMA) since it is the ratio of two distances which does not involve friction.

Efficiency (η): In a real machine, not all of the input work (energy) is available as output work. Some of the energy transferred by the work may be “lost” to other forms such as heat energy due to friction. For this reason, the output work is less than the input work. As a result, the machine is less efficient at accomplishing the task. The efficiency of a machine is defined as the ratio of output work (W_{out}) to input work (W_{in}).

$$\text{efficiency} = \frac{\text{Work output}}{\text{Work input}} \times 100\ \%$$

$$\eta = \frac{W_{out}}{W_{in}} \times 100\ \%$$

- Work input (W_{in}) is the work done by the effort force on the machine: $W_{in} = E \times s_E$
- Work output (W_{out}) is the work done by the machine on the load (weight): $W_{out} = L \times s_L$

For an ideal machine, the output work equals the input work, $W_{out} = W_{in}$, its efficiency is 100%. All real machines have efficiencies less than 100%.

$$W_{out} = W_{in}$$

or $L \times s_L = E \times s_E$

This equation can be written

$$\frac{L}{E} = \frac{s_E}{s_L}$$

We can express the efficiency in terms of the mechanical advantage, MA, and the velocity ratio (ideal mechanical advantage IMA), VR as follows:

$$\eta = \frac{W_{out}}{W_{in}} \times 100\ \% = \frac{L \times s_L}{E \times s_E} \times 100\ \%$$

$$\eta = \frac{L/E}{s_E/s_L} \times 100\%$$

$$\eta = \frac{MA}{VR} \times 100\%$$

Examples

The bottle opener shown in Figure 16 requires that a force of 35 N must be applied to the handle in order to lift the bottle cap 0.90 cm. The opener has a VR of 8 and an efficiency of 75%. (a) What is the MA of the opener? (b) What force is applied to the bottle cap? (c) How far does the handle of the opener move?

Solution

$E = 35$ N $\qquad VR = 8$

$s_L = 0.90$ cm $\qquad \eta = 75\% = 0.75$

To lift (or open) the cap, an effort of 35 N is required. The bottle cap is the load and it moves 0.90 cm.

(a) To find the MA, we use the equation of efficiency.

$$\eta = \frac{MA}{VR} \times 100\%$$

Why not we use the equation $MA = L/E$? The load to be lifted (in this case the cap) is not given.

Rearranging the above equation, we solve for MA as follows:

$$MA = \frac{\eta \times VR}{100\%} = \frac{75\% \times 8}{100\%} = \frac{600}{100}$$

MA = 6

Notice that MA has no units. It indicates the amount that the machine has increased the effort.

(b) From the equation MA = L/E, we solve for the load L.

L = MA × E

L = 6 × 35 = 210 N

Note that by exerting an effort of only 35 N, we can open the bottle cap that has a load of 210 N. This machine multiples the effort 6 times.

(c) The distance the handle moves is sE. This can be determined using the equation of VR.

$$VR = \frac{s_E}{s_L}$$

$s_E = VR \times s_L$

$s_E = 8 \times 0.90\ cm = 7.20\ m$

Examples

An effort of 50 N is moved 6.00 m while lifting a weight of 180 N to a height of 1.50 m using a certain simple machine. Calculate (a) the MA, (b) the VR and (c) the efficiency of the machine.

Solution:

E = 50 N L = 180 N

$s_E = 6.00$ m $s_L = 1.50$ m

(a) The mechanical advantage of the machine is

$$MA = \frac{L}{E} = \frac{180\ N}{50\ N} = 3.6$$

(b) VR (or Ideal Mechanical Advantage, IMA) is distance ratio.

$$VR = \frac{s_E}{s_L} = \frac{6.00\ m}{1.50\ m} = 4$$

From the definition of efficiency, we have

$$\eta = \frac{MA}{VR} \times 100\%$$

$$\eta = \frac{3.6}{4} \times 100\% = 0.9 \times 100\%$$

$\eta = 90\%$

Examples

The efficiency of a certain machine is 80%. What is the work needed to raise a box of mass 200 kg a distance of 6 m? (Use $g = 10\ m/s^2$)

Solution

The work needed to raise the box is the output work (work done by the machine).

$W_{out} = L \times s_L$

$W_{out} = mg \times s_L$

$W_{out} = 200\ kg \times 10\ m/s^2 \times 6\ m = 12,\ 000\ J$

$\eta = 80\%$

From the definition of efficiency, we solve for W_{in}:

$$W_{in} = \frac{W_{out} \times 100\%}{ç} = \frac{1200\ J \times 100\%}{80\%}$$

$W_{in} = 1500J$

The Six Basic Simple Machines

Most machines, no matter how complex, are combinations of one or more of the six simple machines. In the next few pages, each of these simple machines will be discussed separately.

Levers

A lever is a simple machine consisting of a bar that pivots at a fixed point, called a fulcrum. The lever is used to move or raise a large load with a small effort. There are three types (orders) of levers depending on the relative positions of the effort (E), the load (L), and the fulcrum or pivot (P).

1st order lever is used to lift a heavy load with a small force. The fulcrum is between the load and the effort (Figure 18). The crowbar and scissors are examples of first order levers (Figure 19).

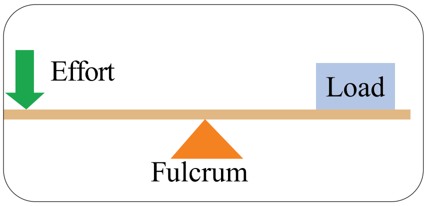


Figure 18.

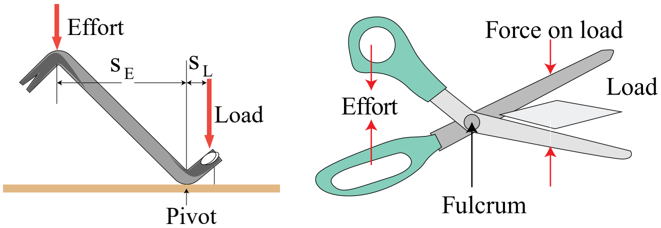


Figure 19.

2nd order lever In a second order lever, the load is between the fulcrum and the effort, as shown in Figure 20. Bottle opener and wheel barrow are examples of second order levers (Figure 21).

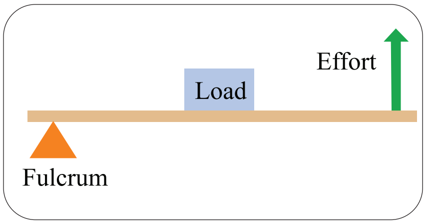


Figure 20.

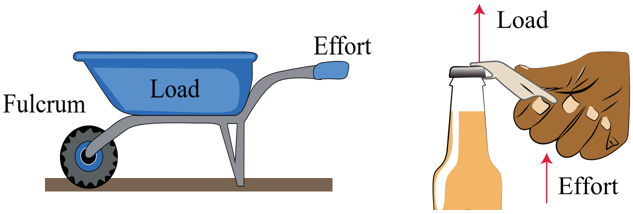


Figure 21.

3rd order lever The effort is applied between the fulcrum and the load (Figure 22). Tongs and human forearm are examples of third order lever (Figure 23).

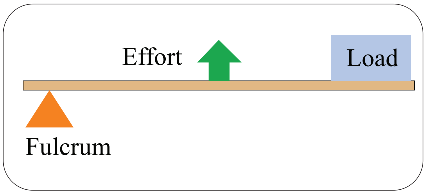


Figure 22.

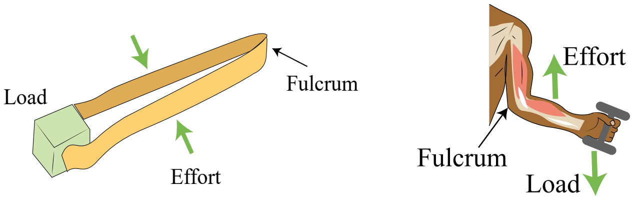


Figure 23.

Examples

The lever shown in Figure 24 has a velocity ratio of 4. A 180 N load is raised by applying an effort of 60 N. If the effort is 1.20 m from the fulcrum, find (a) the distance moved by the load, (b) the MA and (c) the efficiency of the machine.

Solution:

VR = 4 E = 60 N (a) s_L =? (c) η =?

L = 180 N s_E = 1.20 m (b) MA =?

(a) This is the 1st order lever where the pivot is between Load and effort. Solving the VR equation for s_L, we get

$$VR = \frac{s_E}{s_L}$$

$$s_L = \frac{s_E}{VR} = \frac{1.20\text{ m}}{4} = 0.30\text{ m} = 30\text{ cm}$$

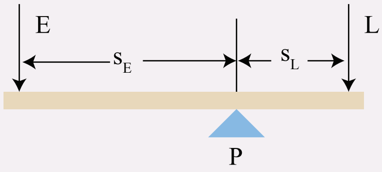


Figure 24.

(b) The actual mechanical advantage MA, is

$$MA = \frac{L}{E} = \frac{180\text{ N}}{60\text{ N}} = 3$$

(c) Using the efficiency equation for simple machines, we get

$$\eta = \frac{MA}{VR} \times 100\%$$

$$\eta = \frac{3}{4} \times 100\% = 0.75 \times 100\%$$

$$\eta = 75\%$$

Examples

A person does 100 J of work in pulling out a nail with a claw hammer. If the hammer does 70 J of work, what is the hammer's efficiency?

Solution:

W_{in} = 100 J η =?

W_{out} = 70 J

The efficiency of this machine is

$$\eta = \frac{W_{out}}{W_{in}} \times 100\ \% = \frac{70\ J}{100\ J} \times 100\ \% = 0.7 \times 100\%$$

$$\eta = 70\%$$

Notice that the person does 100 J of work to operate the machine, claw hammer in this case, and the machine does 70 J of work to pull out the nail. So, the output work is less than the input work due to friction.

Examples

The lever is an efficient simple machine, because there is very little friction at the fulcrum. Using a 90% efficient lever, what input work is required to lift an 18 kg object through a distance of 50 cm? (Use $g = 10\ m/s^2$)

Solution:

$\eta = 90\% = 0.90$ $\quad s_L = 0.50$ m

$m = 18$ kg $\quad W_{in} = ?$

First, we determine the work output (W_{out}) as follows:

$W_{out} = L \times s_L = (mg) \times s_L = (18\ kg \times 10\ m/s^2) \times 0.50\ m = 90\ J$

Where the load to be lifted is the weight of the object, $L = mg$.

Now, using the efficiency equation, we solve for W_{in}.

$$W_{in} = \frac{W_{out}}{\eta} \times 100\% = \frac{90\ J}{90\%} \times 100\%$$

$$W_{in} = 100\ J$$

Activity 1

To make a second order lever, you need the following materials: meterstick, spring balance, some weights, a triangular piece of wood (fulcrum).

First, mark the reading of the spring balance not to include the weight of the meterstick. Then, hang a weight to the meterstick and read the spring balance (Figure 25). After this measure the load and effort distances from the fulcrum and note them. Repeat the above step for different weights.

In this activity you will see that: $L \times s_L = E \times s_E$. This lever has a mechanical advantage because heavy loads can be lifted with small forces.

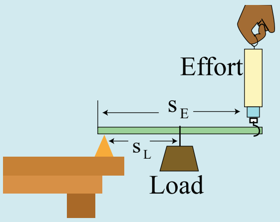


Figure 25.

Note:

Distances are always measured from the pivot point (or fulcrum).

Pulleys

A pulley is a simple machine consisting of a grooved wheel that holds a rope or a cable. A load is attached to one end of the rope, and an effort force is applied to the other end. Basically, we have two kinds of pulleys. These are fixed pulley (Figure 26 (a)) and movable pulley (Figure 26 (b)). Fixed and movable pulleys can be combined to form a block and tackle.

Fixed Pulleys These kind of pulleys only change the direction of a force. Fixed pulleys do not multiply force (Figure 26 (a)). A fixed pulley is attached to something that does not move. By using a fixed pulley, we can pull down on the rope in order to lift the load up, such as a flag. This is usually easier than trying to lift the load straight up. Elevators make use of fixed pulleys. For single fixed pulley, neglecting friction,

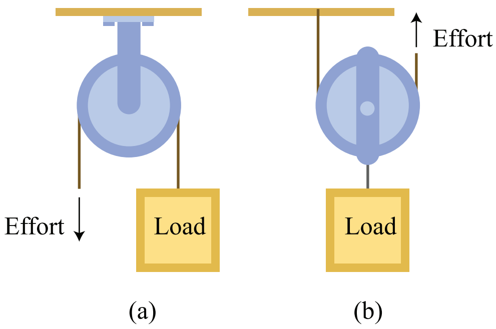


Figure 26.

(i) Load = Effort and hence the MA equals 1.

(ii) $s_E = s_L$ and hence the VR equals 1.

Movable Pulleys Unlike fixed pulleys, movable pulleys are attached to the object being moved (Figure 27 (b)). A movable pulley does not change a force's direction. Movable pulleys multiply force, but you must exert the input force over a greater distance than the load is moved. This is because you must make both sides of the rope move in order to lift the load. For a single movable pulley, neglecting friction

(i) $\text{Effort} = \frac{1}{2}(\text{Load})$, which gives $\text{MA} = \frac{\text{Load}}{\text{Effort}} = \frac{\text{Load}}{\frac{1}{2}(\text{Load})} = 2$

(ii) $s_L = ½\, s_E$. For example, when the effort moves 2 m, the load moves only 1 m. This gives a velocity ratio of 2. That is, $\text{VR} = \frac{s_E}{s_L} = \frac{s_E}{\frac{1}{2}s_E} = 2$

Note

1. The number of strings that support the movable pulley is equal to the VR.
2. If friction is neglected, MA = VR. Therefore, movable pulley is a force multiplier.

Examples

(a) What is the effort force needed to raise the load shown in Figure 27? (b) If we pull the rope downwards by 4 m, how far does the load rise and what is the mechanical advantage of the system?

Solution:

$L = 200$ N (a) Effort force, E =?

$s_E = 4$ m (b) Distance moved by the load, s_E =?

(a) For the fixed pulley, E = L, and for the movable pulley, E = ½ L. Therefore, for this pulley system,

$E = ½ L = ½ \times 200$ N $= 100$ N

(b) For ideal situation, efficiency is 100%. This gives

$W_{in} = W_{out}$

$E \times s_E = L \times s_L$

$100 \text{ N} \times 4 \text{ m} = 200 \text{ N} \times s_L$

$s_L = 2$ m

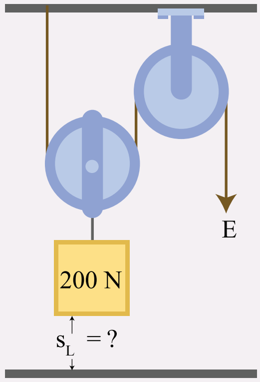


Figure 27.

Block and Tackle - When a fixed pulley and a movable pulley are used together, the pulley system is called a block and tackle. A block and tackle can have a large mechanical advantage if several pulleys are used. In Figure 29, there are two movable and two fixed pulleys. The number of strings supporting the movable pulleys are four. Therefore,

$$VR = \frac{s_E}{s_L} = 4$$

This means that the effort moves four times that the load moves.

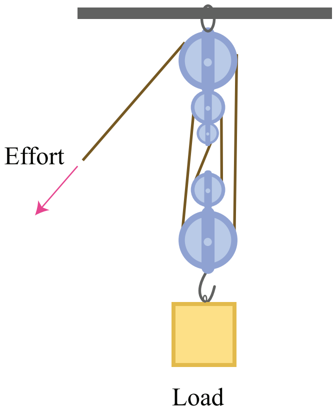


Figure 28.

Examples

The force needed to lift the load in Figure 28 is 10 N. (a) Find the load and the mechanical advantage of the pulley system. (b) How far must the rope be pulled to raise the load by 2 m vertically? (Ignore the weights of pulleys.)

Solution:

$E = 10$ N (a) E =? and MA =?

$s_L = 2$ m (b) s_E =?

(a) From the figure we see that four ropes lift the load. So, $E = \frac{L}{4}$

$L = 4 \times E = 4 \times 10\ N = 40\ N$ and the mechanical advantage, MA, is

$$MA = \frac{L}{E} = \frac{40\ N}{10\ N} = 4$$

(b) Assuming the pulley system to be frictionless,

$W_{in} = W_{out}$

$L \times s_L = E \times s_E$

$40\ N \times 2\ m = 10\ N \times s_E$

$s_E = 8\ m$

Examples

A pulley system lifts a 1400 N weight a distance of 1 m. To do this a person pulls the rope a distance of 4 m, exerting a force of 400 N. (a) What is the VR of the pulley system? (b) What is the MA? (c) How efficient is the machine?

Solution.

$L = 1400\ N$ $\quad$ $s_E = 4\ m$

$s_L = 1\ m$ $\quad$ $E = 400\ N$

(a) Using the velocity ratio (IMA) equation, we get

$$VR = \frac{s_E}{s_L} = \frac{4\ m}{1\ m} = 4$$

(b) The mechanical advantage is

$$MA = \frac{L}{E} = \frac{1400\ N}{400\ N} = 3.5$$

(c) Efficiency of the pulley system is

$$\eta = \frac{MA}{VR} \times 100\%$$

$$\eta = \frac{3.5}{4} \times 100\%$$

$\eta = 87.5\%$

Examples

A system of pulleys has a velocity ratio of 8 and a mechanical advantage of 6. The system is used to raise a load of 3000 N through a distance of 10 m. Calculate (a) the work done on the load, (b) the effort required, (c) the distance moved by the effort, (d) the work done by the effort, and (e) the efficiency of the machine.

Solution:

VR = 8 L = 3000 N

MA = 6 s_L = 10 m

(a) The work done on the load is the work output. Thus,

$W_{out} = L \times s_L$

$W_{out} = 3000\text{ N} \times 10\text{ m} = 30{,}000\text{ J}$

(b) The effort is obtained using the equation of MA.

$$MA = \frac{L}{E}$$

$$E = \frac{L}{MA} = \frac{3000\text{ N}}{6} = 500\text{ N}$$

(c) From the definition of VR, we solve for s_E

$s_E = VR \times s_L = 8 \times 10\text{ m} = 80\text{ m}$

(d) The work done by the effort is the work input. Thus,

$W_{in} = E \times s_E$

$W_{in} = 500\text{ N} \times 80\text{ m} = 40\ 000\text{ J}$

(e) We have two alternatives to find the efficiency. These are:

$$\eta = \frac{W_{out}}{W_{in}} \times 100\% \quad \text{or} \quad \eta = \frac{MA}{VR} \times 100\%$$

$$\eta = \frac{30{,}000\text{ J}}{40{,}000\text{ J}} \times 100\% \qquad \eta = \frac{6 \times 100\%}{8}$$

$$\eta = 75\% \qquad \eta = 75\%$$

ACTIVITY 2

To set up movable pulley system you need the following materials: a pulley, string, a spring balance, meterstick and a 100 g mass.

Adjust the spring balance to zero, without hanging any load on the pulley as in Figure 29 (a). Then hang a 100 g mass on the pulley and read the spring balance (Figure 29 (b)). A 100 g mass weighs about 1 N. Compare the result with its real weight.

Is the reading exactly half of the real weight?

Next, pull the string 20 cm upwards and measure how far the load is raised.

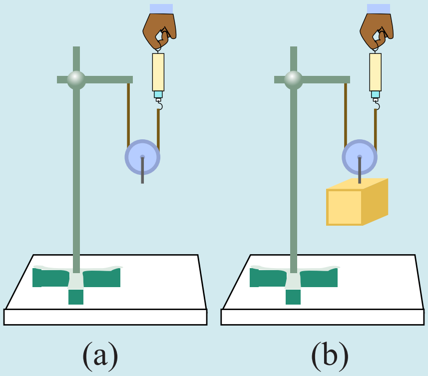


Figure 29.

Inclined Plane

This is one of the most familiar types of simple machines. An inclined plane (ramp) is a flat, sloped surface. A heavy object can be raised by pulling it along an inclined surface instead of lifting it vertically. In Figure 30, we see that as the effort E moves along the inclined plane pulling the object a distance s, the object (Load) is raised a vertical height h. The velocity ratio is then

$$VR = \frac{s_E}{s_L}$$

but $s_E = s$ and $s_L = h$

$$VR = \frac{s}{h}$$

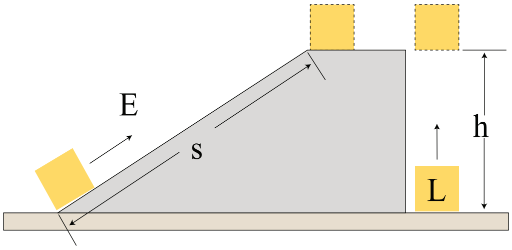


Figure 30.

Examples

The ramp shown in Figure 31 is 18 m long and 4.5 m high. If an effort force of 75 N is required to slide a 255 N box slowly to the top of the ramp, what are (a) the MA, and (b) the efficiency of the ramp?

Solution:

$s = 18$ m $E = 75$ N (a) MA =?

$h = 4.5$ m $L = 255$ N (b) η =?

Notice that the length of the ramp is 18 m. This is the distance the effort moves. The load (box) is raised only a height of 4.5 m.

(a) The mechanical advantage of the ramp is, therefore,

$$MA = \frac{L}{E} = \frac{255\ N}{75\ N} = 3.4$$

(b) First, we have to calculate VR.

$$VR = \frac{s}{h} = \frac{18\ m}{4.5\ m} = 4$$

$$\text{Now, } \eta = \frac{MA}{VR} \times 100\%$$

$$\eta = \frac{3.4}{4} \times 100\% = 85\%$$

Examples

Imagine having to lift a box weighing 1,500 N to the back of a truck that is 1 m off the ground. You would have to exert a force of 1,500 N, the weight of the box, over a distance of 1 m, which equals 1,500 J of work. Now suppose that instead you use a 5 m long ramp, as shown in Figure 31. Calculate the effort force needed to move the load along the 5 m ramp.

Solution:

$L = 1500\ N \qquad E = ?$

$s_E = s = 5\ m$

$s_L = h = 1\ m$

The input work is equal to the output work.

$W_{in} = W_{out}$

$E \times s = L \times h$

$$E = \frac{L \times h}{s} = \frac{1500\ N \times 1\ m}{5\ m} = 300\ N$$

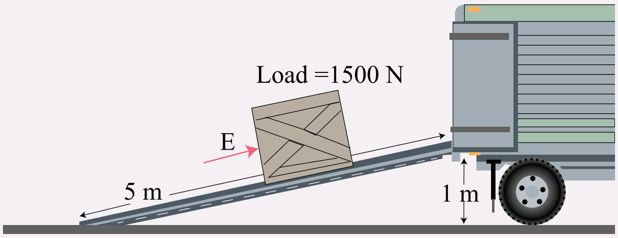


Figure 31.

Notice that the amount of work you need to do does not change. However, the distance over which you exerted the effort force becomes 5 m. Because you exerted the effort force over a distance that is five times as long, the effort you exerted became five times less. Thus, the mechanical advantage of the inclined plane is 5.

Examples

An inclined plane is used to raise a load of 5000 N a height of 6 m. The efficiency of the machine is 75%. If the load moves a distance of 16 m along the plane, find (a) the work done by the plane, and (b) the effort applied on the load.

Solution:

$L = 5000\ \text{N}$ $\qquad \eta = 75\%$

$s_L = 6\ \text{m}$ $\qquad s_E = 16\ \text{m}$

(a) The work done by any machine is the output work.

$W_{out} = L \times s_L = 5000\ \text{N} \times 6\ \text{m}$

$W_{out} = 30\ 000\ \text{J}$

(b) First, calculate the work input and then using the result, obtain the effort force.

$$\eta = \frac{W_{out}}{W_{in}} \times 100\%$$

$$W_{in} = \frac{W_{out}}{\eta} \times 100\% = \frac{30{,}000\ \text{J} \times 100\%}{75\%} = 40,\ 000\ \text{J}$$

Since $W_{in} = E \times s_E$

$$E = \frac{W_{in}}{s_E} = \frac{40.\ 000\ \text{J}}{16\ \text{m}} = 2500\ \text{N}$$

Activity 3

To measure the force on an inclined plane you need the following materials: three or more books, spring balance, a wooden block, a wooden board with smooth surface and string.

Arrange the materials to make an inclined plane as shown in Figure 32. Measure the weight of the block. Then place the block on the plane and pull it up along the plane. Read the scale of the spring balance. What do you observe? What is the mechanical advantage?

Discuss: In which case do you use less force; when you pull the load vertically upwards, or when you pull the load over the inclined plane?

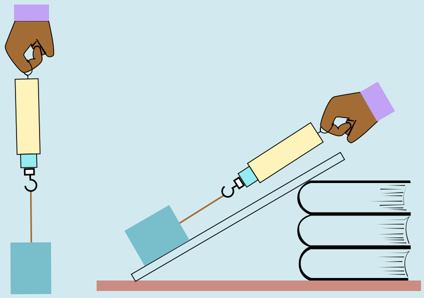


Figure 32.

Wedge

A wedge is a double inclined plane which is sharp at one edge than the other one. Wedges are used to cut materials. A knife, axe, chisel, saw and other cutting tools are examples of wedges.

Consider a wedge used to split a wood (Figure 33 (a)). As the wedge moves down into the wood, the wood splits horizontally a distance equal to the thickness, t, of the wedge as shown in Figure 33 (b). Therefore,

$$s_L = t$$

The effort moves down along the length of the wedge.

$$s_E = L$$

The velocity ratio of the wedge is then,

$$VR = \frac{s_E}{s_L}$$

$$VR = \frac{b}{t}$$

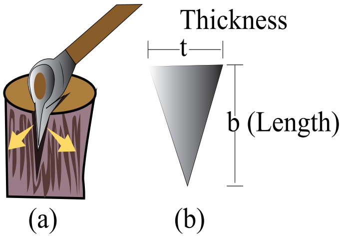


Figure 33.

Examples

A hammer is used to drive a wedge into a log to split it. When the wedge is driven 20cm into the log, the log is separated a distance of 5 cm. A force of 19 000 N is needed to split the log, and the hammer exerts a force of 9 500 N. Calculate (a) the VR of the wedge, (b) the MA of the wedge, and (c) the efficiency of the wedge as a machine.

Solution:

b = 20 cm (distance moved by effort) L = 19000 N

t = 5 cm (distance moved by log (load)) E = 9500 N

(a) As the wedge moves into the wood a distance of 20 cm, the log is separated a distance of 5 cm. Therefore,

$$VR = \frac{b}{t} = \frac{20\text{ cm}}{5\text{ cm}} = 4$$

(b) For any machine, mechanical advantage is given by

$$MA = \frac{L}{E} = \frac{19{,}000\text{ N}}{9{,}500\text{ N}} = 2$$

(c) The efficiency of the wedge is

$$\eta = \frac{MA}{VR} \times 100\% = \frac{2}{4} \times 100\% = 50\%$$

Notice that the longer and thinner wedges have greater mechanical advantages.

Screw

A screw is an inclined plane that is wound around a cylinder or cone to form spiral. A screw is a simple machine that can be used to raise and lower weights as well as to fasten objects. A screw is used to multiply force. Examples of screws include drills, jar lids, and nuts and bolts. The distance between the threads of a screw is called the pitch (p) of the screw (Figure 34 (a)).

To find the velocity ratio, consider the screw jack (a type of screw) shown in Figure 34 (b). If it is turned once by the effort exerted on the handle, the load will rise a distance equal to the pitch of the screw. Thus,

$$s_L = \text{pitch (p)}$$

and the effort moves around the circumference,

$$s_E = \text{circumference}$$

$$s_E = 2\pi \times (\text{length of the handle, l})$$

$$s_E = 2\pi l$$

The velocity ratio of the screw is:

$$VR = \frac{s_E}{s_L}$$

$$VR = \frac{2\pi l}{p}$$

Note that the pitch is less than the number of threads by one.

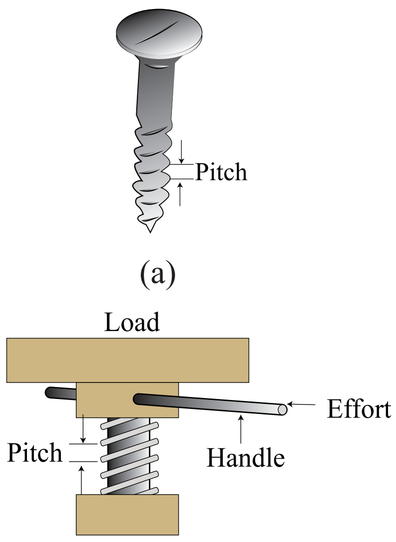


Figure 34.

Examples

The handle of a screw is 1m long. If the pitch of the screw is 1cm, find the VR of the screw as a machine.

Solution

L = 1 m (Length of the handle)

P = 1 cm = 0.01m (Distance between threads)

Using the equation of VR for the screw, we get

$$VR = \frac{2\pi l}{p} = \frac{2 \times 3.14 \times 1\ m}{0.01\ m} = 628$$

Wheel and axle

A wheel and axle consists of two circular objects of different sizes that are attached in such a way that they rotate together. As shown in Figure 35 (a), the larger object of the faucet is the wheel and the smaller object is the axle. Doorknobs, wrenches, screwdrivers, and steering wheels (in all cars) all use a wheel and axle.

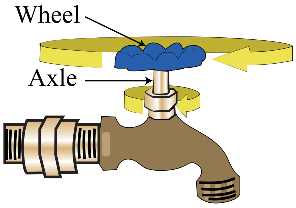
When a small effort force is applied to the wheel, it rotates through a circular distance of radius R. As the wheel turns, so does the axle (Figure 35 (b)).

But because the axle is smaller than the wheel, it rotates through a smaller circular distance of radius r. The velocity ratio of the wheel and axle is, then

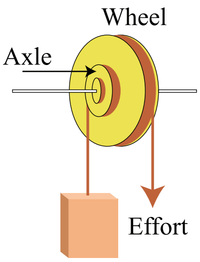
$$VR = \frac{s_E}{s_L}$$

$$VR = \frac{2\pi R}{2\pi r}$$

$$VR = \frac{R}{r}$$



(a)



(b)

Figure 35.

Examples

The wheel and axle machine shown in Figure 36 has axle radius of 30 cm and wheel radius of 60 cm. What is the velocity ratio of the machine?

Solution:

r = 30 cm VR =?

R = 60 cm

The velocity ratio is $VR = \frac{R}{r} = \frac{60\ cm}{30\ cm} = 2$

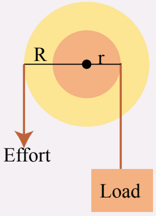


Figure 36.

Compound Machines

Most machines, no matter how complex, are combinations of one or more of the six simple machines: the lever, pulley, wheel and axle, inclined plane, wedge, and screw. A machine consisting of two or more simple machines linked in such a way that the load of one machine becomes the effort force of the second is called a compound machine.

For example, consider the can opener shown in Figure 37 (a). The axle has gear teeth on it that grip the can and act as tiny levers to push the can along when the axle turns.

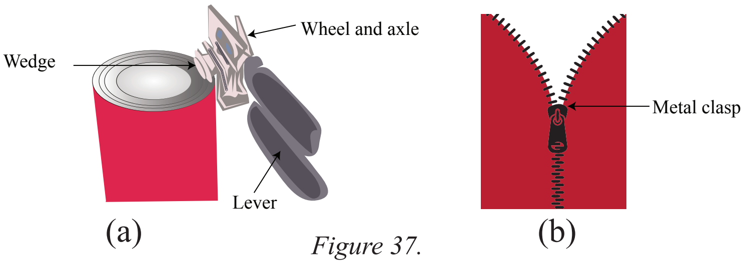


Figure 37.

Inside the metal clasp of the zipper shown in Figure 37 (b) are three wedges. One wedge opens the zipper by splitting the teeth apart. Two other wedges close the zipper by pushing the teeth together.

Discuss 6:

1. List five machines (simple or/ and compound) that you have encountered in your day-to-day life and indicate what type of machine each is.
2. Classify the tools shown in Figure 38 as a lever, a wheel and axle, an inclined plane, a wedge, or a pulley. (a) clothes peg, (b) plier, (c) hole punch, (d) saw, (e) mixer, (f) steel punch, and (g) metal plumber.

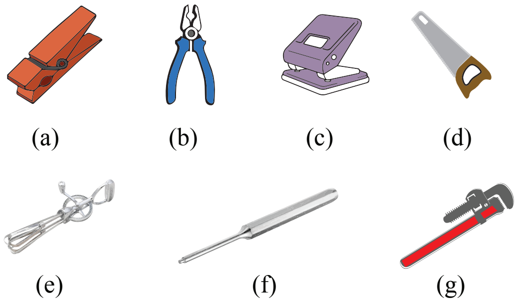


Figure 38.

SUMMARY

3.1 Work, Energy, and Power

Work

- In the simplest case work is done when a force is applied to an object and the object moves in the direction of the applied force.

  $W = Fs$

- Only the component of the force in the direction of the displacement does work.

  $W = Fs \cos \theta$

  - If the displacement is zero, then so is the work.
  - The SI unit of work and energy is the joule (J), where 1 J = 1 N.m.

Kinetic energy

- Kinetic energy is the energy due to motion.
- Kinetic energy increases linearly with mass and with the square of the velocity.

  $KE = \frac{1}{2} mv^2$

- The total work done on an object equals the change in its kinetic energy.

  $W = \Delta KE = KE_f - KE_i$

Potential energy

- Energy stored for later use is potential energy.
- The potential energy of an object is determined by the amount of work required to move it from one location to another.

  $PE = mgh$

Conservation of Energy

- In an ideal system (with no form of friction), energy is transformed from potential energy to kinetic energy and vice versa, but the sum of the two is constant.
- The sum of the potential and kinetic energies of an object is its mechanical energy, ME.

  $ME = PE + KE$

Power

- Power is the rate at which work is done.

  $p = \frac{W}{t}$ and $p = Fv$

- The faster work is done, the greater the power.

- The SI unit of power is the watt (W), where 1 W = 1 J/s.
    - Horsepower (hp) is defined as: 1 hp = 746 W

3.2 Machines

- Simple machines do not change the amount of work done, but they do make the task easier.
- A machine can be used to (i) multiply force, (ii) change the direction of the applied force (effort), or (iii) multiply speed.
- The mechanical advantage, MA, is the ratio of load to effort force.

$$MA = \frac{L}{E}$$

- The ideal mechanical advantage, or velocity ratio, is the ratio of the distance moved by the effort to the distance moved by the load.

$$VR = \frac{s_E}{s_L}$$

- The efficiency of a machine is the ratio of output work to input work.

$$\eta = \frac{W_{out}}{W_{in}} \times 100\% \quad \text{or} \quad \eta = \frac{MA}{VR} \times 100\% = \frac{L \times s_L}{E \times s_E} \times 100\%$$

Exercises

(i) Multiple Choice Questions

1. How much work is done when a force of 30 N moves an object a distance of 3 m?
   (a) 3 J (b) 10 J (c) 30 J (d) 90 J
2. The unit of work, Joule, is the same as
   (a) Newton/second (N/s)
   (c) Newton × second (N.s)
   (b) Newton /kilogram (N/kg)
   (d) Newton × Meter (N.m)
3. For a particular force and displacement, the most work is done when the angle between them is
   (a) 30^o (b) 60^o (c) 90^o (d) 180^o
4. A certain truck has twice the mass of a car. Both are moving at the same speed. If the kinetic energy of the truck is KE, the kinetic energy of the car is
   (a) KE/4
   (b) KE/2
   (c) KE

(d)

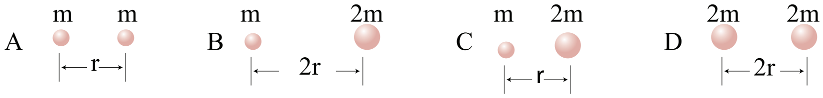


Figure 39.

(e) 2KE

5. Which of the following objects has the largest kinetic energy?
   (a) Mass 3m and speed v.
   (b) Mass 3m and speed 2v.
   (c) Mass 2m and speed 3v.
   (d) Mass m and speed 4v.
6. A 7 kg ball falls from a 2 m high shelf. Just before hitting the floor, what will be its kinetic energy? (Use $g = 10\ m/s^2$)
   (a) 14 J (b) 20 J (c) 30 J (d) 140 J
7. Which of the following is that form of energy associated with an object's position?
   (a) Potential energy
   (b) Kinetic energy
   (c) Sound energy
   (d) Light energy
8. What is the kinetic energy of a 0.135 kg basketball thrown at 40 m/s?
   (a) 216 J (b) 108 J (c) 87 J (d) 54 J
9. If the velocity of a moving ball is tripled, the kinetic energy of the ball is increased by a factor of
   (a) 30 (b) 27 (c) 9 (d) 6
10. No kinetic energy is possessed by
    (a) a shooting star
    (b) a flowing water
    (c) a pendulum at the bottom of its swing
    (d) a block placed on top of a building.
11. An object thrown vertically upwards will rise until
    (a) its kinetic energy becomes zero
    (b) its potential energy becomes zero
    (c) both its kinetic and potential energies reach a maximum value
    (d) both its kinetic and potential energies reach a minimum value.
12. As an object falls freely, there is a decrease in its
    (a) velocity
    (b) acceleration
    (c) kinetic energy
    (d) potential energy
13. Which of the following is not a unit of power
    (a) J/s (b) W.s (c) W (d) hp

14. A 200 hp engine can deliver, in SI units, an average power of
    (a) 200 W (c) 149,000 W
    (b) 74,600 W (d) 298,000 W
15. Which one of the following statements about a simple machine is true?
    (a) It multiplies power (c) It multiplies force and speed
    (b) It multiplies energy (d) It multiplies force
16. Which of the following cannot be increased by using any machine?
    (a) Force (c) Work
    (b) Speed (d) Distance
17. What is the mechanical advantage of a simple machine that changes only the direction of the effort force?
    (a) less than 1 (c) zero
    (b) 1 (d) greater than 1
18. Which one of the following statements about a simple machine is true?
    (a) It multiplies power (c) It multiplies force and speed
    (b) It multiplies energy (d) It multiplies force
19. Which of the following cannot be increased by using any machine?
    (a) Force (c) Work
    (b) Speed (d) Distance
20. A boy weighs 400 N. If he lifts a car of weight 20,000 N by applying his weight on a lever, what must be the mechanical advantage of the lever?
    (a) 0.5 (b) 0.02 (c) 50 (d) 20
21. What do we mean when we say that a certain machine is 98 percent efficient?
    (a) The machine multiplies an input force by a factor of 98.
    (b) The machine multiplies an input energy by a factor of 98.
    (c) The machine wastes 2 joules of an input energy
    (d) The machine wastes 2 percent of an input energy
22. A force of 50 N is needed to raise a 240 N load with a pulley system. The load goes up 1m for every 5 m of the rope pulled through the pulleys. What is the efficiency of the pulley system?
    (a) 50% (b) 48% (c) 96% (d) 98%
23. The efficiency of an inclined plane used as a machine to raise load is 50%. If the inclined plane has a length of 4 m and a height of 1 m, what is its mechanical advantage?
    (a) 3 (b) 2 (c) 5 (d) 4

(ii) Conceptual Questions

24. When does a force do work?
25. Give two examples in which a force acts on an object, but the work done by that force is zero.
26. What happens to the gravitational force between two masses if their separation is halved?
27. Is it possible to get more work out of a machine than you put into it?

(iii) Problems

28. If a person does 50 J of work in moving a 30 kg box over a 10 m distance on a horizontal surface, what is the minimum force required?
29. A 1200 kg automobile travels at 90 km/h. (a) What is its kinetic energy? (b) What amount of work would be required to bring it to a stop?
30. How long does it take a worker producing 200 W of power to do 10,000 J of work?
31. An elevator is able to raise 1000 kg to a height of 40 m is 16 seconds. What is the elevator's power output?
32. How much more gravitational potential energy does a 1.0 kg hammer have when it is on a shelf 1.2 m high than when it is on a shelf 0.90 m high?
33. A force of 300 N is used to push a 120 kg mass 30 m horizontally in 3.00 s. Calculate(a) the work done on the mass, and (b) the power developed.
34. If an automobile engine delivers 50 hp of power, how much time will it take for the engine to do 6.40×10^5 J of work? (1 hp = 746 W)
35. (a) What is the kinetic energy of an automobile with a mass of 1250 kg traveling at a speed of 11 m/s? (b) What speed would a fly with a mass of 0.55 g need in order to have the same kinetic energy as the automobile.
36. Two identical objects move with speeds of 5.0 m/s and 25.0 m/s. What is the ratio of their kinetic energies?
37. An effort of 80 N lifts a load of 100 N using a machine having a VR of 2. What is the efficiency of the machine?
38. A man raises a 500 N stone by means of a lever 5 m long. If the fulcrum is 1 m from the end that is in contact with the stone, what is the VR?
39. An inclined plane is 4 m long and one end is 1m higher than the other. A force of 300 N parallel to the ramp is needed to slide an 80 kg box up slowly. (a) Find the work done by the effort in moving the box up the plane. (b) Find the efficiency of this machine.
40. A system of pulleys is to lift 800 N load by applying 400 N effort. If the effort moves through a distance of 10 m, the load rises to a height of 2 m. Find (a) the MA, (b) the VR, (c) the work done on the load (d) the efficiency of the machine.
41. A screw jack has a pitch of 1cm, and the effort is applied at the end of a handle 25 cm long. What is the VR of this machine?

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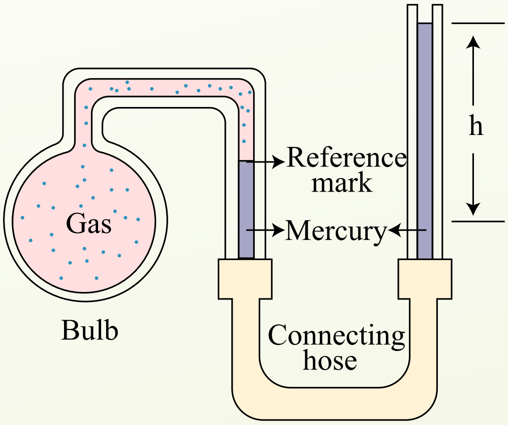
CHAPTER 4

THERMAL PHYSICS

Chapter Contents



Chapter Outcome

Learners are able to:

- elaborate the concept of heat, its relationship with temperature and its effects on substances in accordance with the Gas Laws.

Introduction

Heat and temperature are inter-related, but contrary to the belief of the society, they do not mean the same thing. The reason why the concept of heat and temperature are mixed up is because they are closely related in real life. Thus, if heat is added to something, its temperature goes up and If the temperature is reduced heat is taken away. Recognizing the distinction between these two seemingly identical quantities leads to a clearer understanding of the world around us. Heat has different effects on matter, such as change in volume, change in temperature change and change in state of matter. In this section, the first two effects have given emphasis. Moreover, you will look at the different thermometers, the different temperature measuring scales and inter-conversion between them, and gas laws.

Upon completion of this topic you will be able to:

- distinguish between Temperature and Heat
- outline the steps and principles involved in the measurement of temperature
- describe the features and use of different types of thermometers.
- identify fundamental intervals of thermometers.

Heating has different effects on matter. Important effects of heating are change in size, change in temperature and change in states of matter (solid to liquid or liquid to gas and vice versa). In this unit we will focus only on the first two effects. You will start by studying differences between heat and temperature, and then you will deal with the different temperature scales, the different thermometers and calibration of thermometers as well.

Types of Heat

1. Sensible heat refers to the heat you can feel or sense. This type of heat can be measured with the help of a thermometer without any change in the state.
2. Latent heat, also called "hidden heat", refers to the energy involved in a change of state which can not be felt.

For example, when water kept in a vessel on a stove starts boiling from 10^{o}C to its boiling point (100^{o}C). The Sensible heat from the flame is causing the temperature of the water to rise without any change in its state. After reaching its boiling point, water starts turning into steam without any change in temperature. This is caused by the latent heat of vaporization of water.

A. Difference between temperature and heat

People use terms heat and temperature interchangeably, as if they were the same thing. But they are completely different concepts – one is energy and the other is a fundamental physical quantity.

KEY TERMS

- Heat is energy in transit due to temprature difference
- Temprature is a measure of the average kinetic energy of the particles within the substance.

What is heat?

You may have been learnt that all particles of matter are always in constant motion. The average speed of particles depends on which state that the object exists. Under the same conditions, gas molecules are faster than that of liquids. Atoms in solids are in constant vibration but cannot move freely within the bulk.

When a substance is heated up, its partcles start to move more rapidly (increase the average kinetic energy) provided that no change in the state of matter (solid to liquid, or liquid to gas) takes place. If there is change in state of matter, the heat supplied to the substance breaks the bond between molecules or atoms by then increasing their potential energy. You can see that in both cases, heating a substance is adding kinetic or potential energy to it. This shows that heat is a form of energy, and it is therefore measured in joules (J).

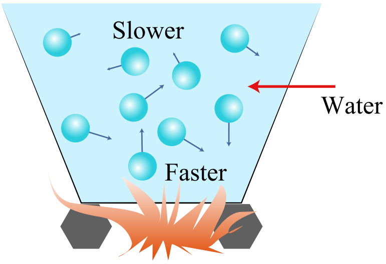


Figure 1. Water boiling

Heating a substance, which does not undergo a phase change, increases its temperature If two objects at different temperatures are brought in contact, energy flows from the hotter object to the cooler one. This energy in transit is called heat. Thus, heat is defined as a form of energy flowing between two objects, which are in thermal contact, due to the difference in their temperatures.

You can understand from the definition that there is no stored heat energy; i.e., we cannot say an object contains this amount of heat stored in it. Once the energy is transferred to a substance, it will be manifested as the total thermal energy inside the substance (sum of the total kinetic and potential energies), and is no more heat energy.Heat is an extensive quantity since it depends on mass.

KEY TERMS

- Thermal contact

  Two objects are said to be in thermal contact if they can exchange heat energy, provided that they may or may not be in physical contact.

What is temperature?

If you touch a substance with your bare hand, you may feel cold or hot. The measure of this property of matter, hotness or coldness, is called temperature. We can agree in that the higher the temperature, the hotter the object, and vice versa. However, "hotness" or "coldness" are subjective sensations and do not define temperature properly. For example, the temperature of the same weather may be hot for one person and cold for another person.

You have learnt above that heating increase both the temperature of the substance and the average kinetic energy of its particles proportionally. Later, it is known that the temperature of a substance depends on the average kinetic energy of its particles.

Temperature is defined as a measure of the average kinetic energy of the particles within the substance.

All particles in a substance cannot have the same speeds at the same temperature. That is why, we say temperature depends on average speed or average kinetic energy. If the average kinetic energy of all particles in a substance is high, then the substance is at a higher temperature. The average kinetic energy of water at 10 °C is smaller than the average kinetic energy of water at 40 °C, as shown in Figure 2.

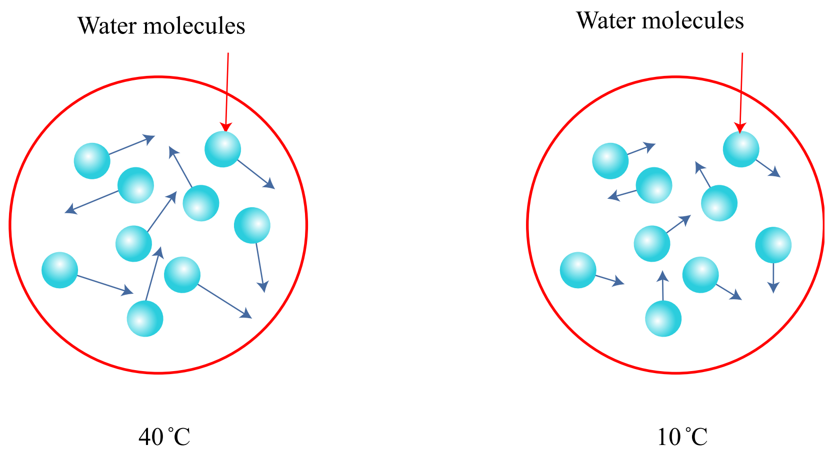


Figure 2. The average kinetic energy of molecules of hot water is greater than that the cold water (Length of arrows indicate speed size)

The temperature of a substance does not depend on the mass and type of the substance and hence it is said to be an intensive property like pressure and density. Temperature is a fundamental physical quantity whose SI unit is Kelvin (K). Other non-SI units of temperature are degree Celsius (°C), and degree Fahrenheit (°F).

ACTIVITY 1

At room temperature all molecules of a gas have the same average kinetic energy. Since kinetic energy of a particle depends on its mass and speed, therefore molecules of smaller masses travel faster than the heavier molecules. why?

Thermal equilibrium

The temperature of a system is a property that determines whether a system is in thermal equilibrium with other systems or not. If you bring a glass of cold water from a fridge and a cup of boiled coffee from a boiler and leave them on a tabletop in the room for a few minutes, then you will find that the two liquids will have the same temperature as that of the room. That is, they both reach thermal equilibrium with the room.

If two objects are brought in thermal contact, heat flows from the hotter object to the cooler one until the two objects attain thermal equilibrium. Two objects in thermal equilibrium do not exchange heat energy.

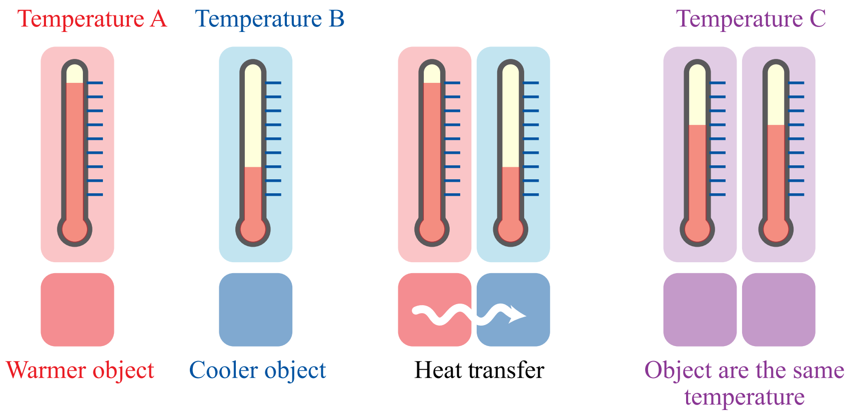


Figure 3. Heat flow ceases after thermal equilibrium

B. Temperature scales

Different temperature scales have been used in the past. The most commonly known scales which scientists now tend to deal with are the Kelvin scale (K), the Celsius scale (°C) and the Fahrenheit scale (°F).

To design a temperature scale two fixed reference points have to be used. Once these points are set,

KEY TERMS

- Absolute zero the temperature at which a substance has no thermal energy. It is unatainable temprature.

we can divide the range into equal divisions in an appropriate interval. For example, in the Celsius scale, the freezing point is the lower fixed reference point and is given as 0 °C. The boiling point of water (100°C) is taken as the upper fixed reference point. The difference between the two fixed points is divided into 100 equal divisions. Each division is called a degree.

Activity 2

The Fahrenheit scale is being obsolete, since it is rarely used by the scientific community. why?

In Kelvin temperature scale, the lowest fixed point is taken to be the absolute zero, 0 K. This temperature corresponds to a temperature of -273.15 °C on the Celsius temperature scale and is unattainable. The absolute zero is the temperature below which temperatures do not exist. In other words, absolute zero is the temperature at which molecular energy is a minimum or particles will not have thermal energy. The freezing point of water in Kelvin scale is 273 K and the boiling point is 373 K. The Kelvin and the Celsius scales are often used together as they have the same scale divisions.

The Kelvin scale is commonly used by scientists because temperatures measured in Kelvin scale are directly proportional to the average kinetic energy of the particles. The Kelvin (K) is taken as the SI unit of temperature. Unlike Celsius and Fahrenheit scales, there is no degree symbol included with K.

In the Fahrenheit scale, the lower fixed point is taken to be the temperature of an ice, water and ammonium chloride mixture. This value is assigned 0 °F and this value in Celsius scale is -32 °C. The upper fixed point in this scale is taken to be the normal body temperature which is 98 °F. In Fahrenheit scale, the freezing point and the boiling point of water are 32 °F and 212 °F, respectively. Thus, the Fahrenheit scale has 180 scale divisions.

The diagram in Figure 4 shows the relationships among the three temperature scales between the absolute zero and the boiling point of water.

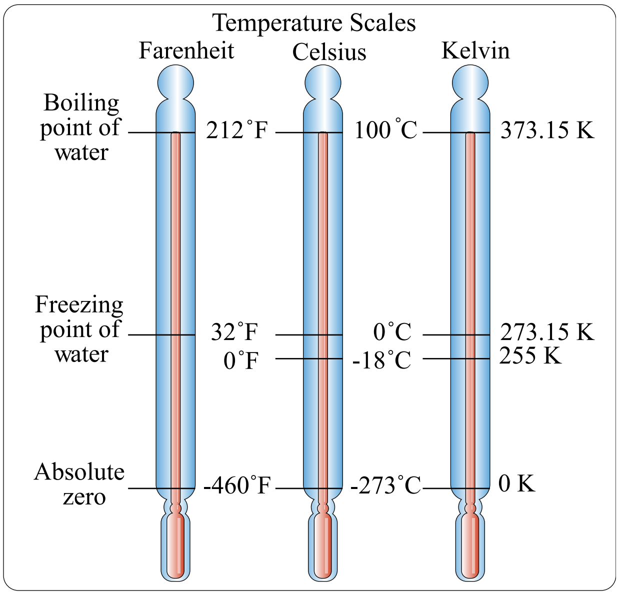


Figure 4. Relationships between the three temperature scales

ACTIVITY 3

Discuss in groups about temperature scales and their relationships.

Inter-conversion of scales

It is also possible to derive mathematical relationships among the three temperature scales. Let the lower and upper fixed points in both scales be the freezing point and boiling point of water, respectively. The temperature at any point in Celsius scale (T_C) and that in Kelvin scale (T_K) can be related as

$$\frac{T_C - \text{The lower fixed point in Celsius}}{T_K - \text{The lower fixed point in Kelvin}} = \frac{\text{Number of divisions in Celsius}}{\text{Number of divisions in Celsius}}$$

$$\frac{T_C - 0}{T_K - 273\,K} = \frac{100°C}{100K}$$

$$T_C = T_K\,(°C/K) - 273\ °C$$

Similarly, the temperature at any point in Celsius scale (T_C) is related to that in Fahrenheit scale (T_F) as

$$\frac{T_C - 0}{T_F - 32°F} = \frac{100°C}{180°F}$$

After some rearrangements, we have.

$$T_F = \frac{9}{5}T_C\,(°F/°C) + 32\ °F$$

Rearranging for T_C gives $T_C = \frac{5}{9}(T_F - 32)$

Examples

What is the temperature of the air in Celsius if it is 100 °C in Fahrenheit?

Solution: $T_F = 100\ °F$

After going some rearrangements on equation $T_F = \frac{9}{5}T_C\,(°F/°C) + 32\ °F$, we obtain

$$T_C = \frac{5}{9}(T_F - 32\ °F)°C/°F$$

$$T_C = \frac{5}{9}(100°F - 32\ °F) = \frac{5}{9}(68\ °F)°C/°F$$

$$T_C = 37.78\ °C$$

Examples

At what temperature do the Kelvin and the Fahrenheit scales read the same value?

Solution: $T_F = T_K$

Combining the above two equations of T_C, we obtain

$$T_K\left(°C/K\right) - 273\ °C = \frac{5}{9}\left(T_F - 32\ °F\right)°C/°F$$

Canceling out $°C$ at both sides of this equation, you obtain

$$T_K\left(1/K\right) - 273 = \frac{5}{9}T_F\left(1/°F\right) - 32$$

Substituting $T_K = T_F$, replacing $°F$ by K and undertaking some steps, we find

$$T_K = T_F = 574.25K = 574.25°F$$

C. Thermometry

An instrument used to measure temperature is known as Thermometer. The name was originated from two Greek words "thermos" which means "hot" and "metron" which means "measure".

1. Types of thermometers and their properties

Thermometric properties and Types of thermometers

There are different types of thermometers used to measure temperature. A thermometer is specified by choosing a particular thermometric substance and a particular thermometric property of that substance. A thermometric property of matter is a property that varies predictably with an increase or decrease in temperature. It could be change of pressure in a gas thermometer, a change in electromotive force in a thermocouple, or the change in height of a liquid in a liquid thermometer. It is assumed that there is a one-to-one relationship between the measured values of that property and the temperature.

Liquid in glass thermometers

Liquid in glass thermometers make use of thermometer liquids inside them. A liquid in glass thermometer consists of

(i) a bulb (reservoir of the thermometer liquid at the bottom),
(ii) a stem or a tube containing the capillary,
(iii) a thermometric liquid and
(iv) an inert gas in the evacuated tube, as shown in Figure 5.

The bulb is filled with a thermometric liquid at 0 °C. When the thermometer is brought in thermal contact with a hotter body, the liquid in the bulb expands and rises up the capillary tube. Since the body of the thermometer is scaled, this allows us to read the temperature directly. The thermometric liquid must be colored so that the reader can tell the temperature during the measurement.

Thermometric liquids, to be used in liquid in glass thermometer should have the following properties.

- Low freezing point
- High boiling point
- Uniform thermal expansion
- Good conductor of heat
- That do not wet glass
- Small specific heat capacity

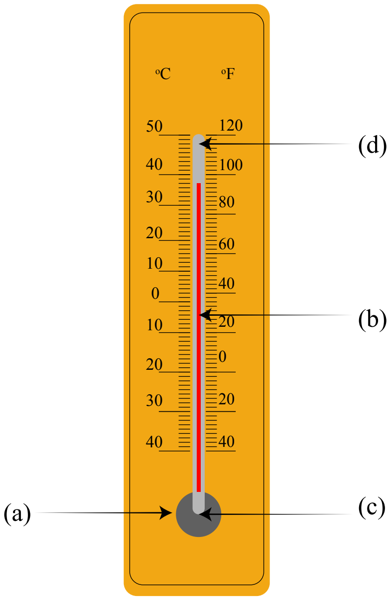


Figure 5. Liquid in glass thermometer

Major liquids that are used in glass thermometers are mercury and alcohol. However, mercury is now being replaced by alcohol due to its toxic nature which poses danger on human health.

2. Calibration of thermometers

By studying responses of properties of objects against the heat supplied to them, we can construct thermometer. Let us see how mercury in glass thermometer can be calibrated.

Mercury in glass thermometers

You have learnt that you need to choose two suitable points to calibrate a thermometer: lower fixed point and upper fixed point. Then divide the interval into equal division of a suitable unit. The two universal points to calibrate a temperature are the triple point of water (273.16 K, 611.73 Pa) and the absolute zero (0 K, 0 Pa). The triple point is the pressure and temperature at which water exists as a gas, liquid and solid simultaneously.

Key Terms

- The **triple point** is the pressure and temperature at which water exists as a gas, liquid and solid simultaneously.

We can calibrate a liquid thermometer for the Celsius scale using the following method.

(i) Place the bulb of an ungraduated thermometer in crushed ice, as shown in Figure 6a. Then, mark the level of the liquid (alcohol or mercury) when it stops rising up the tube. This is the lowest fixed point.

(ii) Place the bulb of the ungraduated thermometer in steam from boiling water, as shown in Figure 6b. Mark the level of the liquid (alcohol or mercury) when it stops moving. This is the upper fixed point.

(iii) Divide the distance between the two fixed points into 100 equal divisions and mark for each interval. The lowest fixed point is at 0 °C and the upper 100 °C.

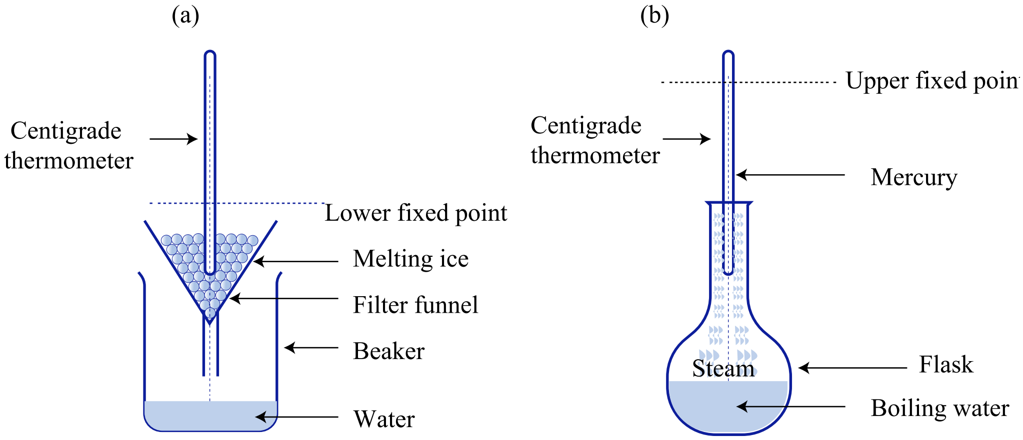
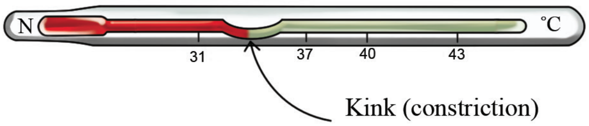


Figure 6. Thermometer calibration

Alcohol thermometer

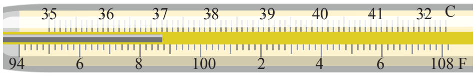
An alcohol thermometer utilizes the expansion and contraction of alcohol in response to temperature changes to measure the temperature. A number of different alcohols can be used, depending on the environment where the thermometer is being utilized, with ethanol being among the most common. This type of thermometer is very popular because it is non-toxic, unlike a mercury-in-glass thermometer, and the contents will not pose a threat to human health or the environment if the thermometer is broken.

Clinical thermometer



The clinical thermometer, commonly know as doctor's thermometer is a liquid-in-glass thermometer with a short temperature range (up to 43°C). It Contains a Kink (Constriction) which helps to hold back the liquid so that the temperature can be read at leisure.

Mercury thermometer



The mercury-in-glass or mercury thermometer consists of a bulb containing mercury attached to a glass tube of narrow diameter; the volume of mercury in the tube is much less than the volume in the bulb. The volume of mercury changes with temperature; the small change in volume pushes the narrow mercury column a relatively long way up the tube. The space above the mercury may be filled with nitrogen gas or a partial vacuum. The mercury thermometer can be dangerous if the glass breaks and the mercury is not cleaned up properly. The mercury will evaporate and can contaminate the surrounding air and become toxic to humans and wildlife.

While measuring the temperature of a substance, if x is the length of mercury above the ice point and y is the fundamental interval, then T, the temperature of the substance is:

$$T = \left(\frac{x}{y}\right) \times 100\ ^{o}C$$

Gas thermometer

A gas thermometer measures the temperature by the variation in volume or pressure of a gas. It contains gas as the enclosed thermometric substance, variations in temperature being indicated by the change in pressure of a fixed quantity of gas required to maintain the gas at a constant volume or the change in volume of a fixed quantity of gas maintained at a constant pressure.

While measuring the temperature of a substance by gas Thermometer, if P_T is the pressure of gas at temperature of body, P_o is the pressure of gas at ice point, P_{100} is pressure off gas at steam point, then temperature of the body is:

$$T = \left[\frac{(P_T - P_0)}{(P_{100} - P_0)}\right] \times 100\ °C$$

Resistance thermometer

Resistance thermometer measures the change in resistance of platinum wire with temperature. It is calibrated against a known standard resistance. Resistance thermometers work by changing resistance with a change in temperature in a repeatable manner. Resistance thermometers are made from platinum wire that is either wrapped around a ceramic or glass core or has been deposited on a ceramic base. Such thermometers are used for measuring environmental temperatures. While measuring the temperature of a substance by resistance thermometer, if R_T

is the resistance at temperature of body, R_o is resistance at ice point, and R_{100} is the resistance at steam point, the temperature of the substance is:

$$T = \left[\frac{(R_T - R_0)}{(R_{100} - R_0)}\right] \times 100\ ^\circ C$$

Bimetallic thermometer

A bimetallic thermometer converts the media's temperature into mechanical displacement using a bimetallic strip. The bimetallic strip consists of two different metals having different coefficients of thermal expansion. Bimetallic thermometers are used in residential devices like air conditioners, ovens, and industrial devices like heaters, hot wires, refineries, etc. They are a simple, durable, and cost-efficient way of temperature measurement. This type of thermometer is less expensive than other thermometers, and they arefully mechanical and do not require any power source to operate. While measuring the temperature of a substance by bimetallic thermometer, if E_T is the emf at the temperature off body, E_o is the emf at ice point, and E_{100} is the emf at steam point, then temperature of the substance is:

$$T = \left[\frac{(E_T - E_0)}{(E_{100} - E_0)}\right] \times 100\ ^\circ C$$

Pyrometer

Pyrometer is used for measuring relatively high temperatures, such as are encountered in hot furnaces. Most pyrometers work by measuring radiation from the body whose temperature is to be measured. Radiation devices have the advantage of not having to touch the material being measured. This type of thermometer can measure the temperature of the object without any contact with the object. Also, it has a fast response time, and good stability while measuring the temperature of the object. Pyrometer is also known as infrared thermometer, or radiation thermometer, or non-contact thermometer.

Thermistor

Thermistor is a resistance thermometer, or a resistor whose resistance is dependent on temperature. The term is a combination of "thermal" and "resistor". It is made of metallic oxides, pressed into a bead, disk, or cylindrical shape and then encapsulated with an impermeable material such as epoxy or glass. A thermistor does not actually "read" anything, instead the resistance of a thermistor changes with temperature. How much the resistance changes, it depends on the type of material used in the thermistor. The thermistors are used in cars to measure oil and coolant temperatures, and in household appliances such as ovens and refrigerators.

Exercises

1. There is no temperature below absolute zero. What would the kinetic energy of a particle at this temperature be? What about its potential energy?
2. In an ideal gas, all molecules have equal kinetic temprature energy (same temprature). Then, can we say that both hydrogen molecule and oxygen molecule have the same speed?
3. Two identical steel spheres have temperatures 200 K and 400 K. What is the key difference in the energy of the atoms of the two spheres? If the two spheres are brought in thermal contact, which atoms speed up and which ones get slower?
4. In most cases, heating a substance results in an expansion in volume. Why?
5. Convert temperatures 32.0 oC, and 80 oF into Kelvin scale.

Upon completion of this topic you will be able to:

- solve simple thermometry problems.
- introduce some applications of thermal expansion.

One of the effects of heating is thermal expansion. Except the abnormal expansion of water between 0 °C and 4 °C temperatures, substances expand when they absorb heat and contract when they release heat. Thermal expansion or contraction occurs spherically in all dimensions but it can be broken down into three categories: linear expansion, surface (area) expansion and volume expansion. In this section, you will learn how to manipulate changes in size of substances by heating. Peculiar behavior of water in response to heating is also treated. Finally, you will see some applications of thermal expansion.

Linear expansion

The change in any linear dimension of a solid, such as its length, width or thickness, is called linear expansion. The change in length of bar is directly proportional to product of the change in temperature and its original length. Suppose the original length of a bar is L_0 when the temperature is T_0, as shown in Figure 7. If the length of the bar is changed to L when the temperature is changed by ΔT, then the change in its length ΔL, is given by

$$\Delta L = \alpha L_0 \Delta T$$

Key Terms

- Thermal expansion increase in size of a substance as a result of heating
- Coefficient of thermal expansion is ratio of the change in length, area or volume in a temperature change of 1 K

where $\Delta T = T - T_0$ and the proportionality constant α, is called the coefficient of linear expansion.

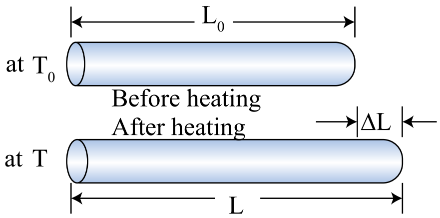


Figure 7. Linear expansion

The coefficient of linear expansion can also be defined as the fractional change in length per unit temperature, $(\alpha = \Delta L / L_0 \Delta T)$ and its unit can be $°C^{-1}$, or K^{-1}.Each solid has a unique linear expansion coefficient; i.e., different substances expand different amounts for the same temperature change.

Coefficients of linear expansion of some selected materials are given in Table 4.1. The coefficient of linear expansion of Aluminum is 2.3 $\times 10^{-5} K^{-1}$ means that if the temperature of 1 m long Aluminum is increased by 1 K, its length increases by 2.3×10^{-5} m. By the same change in temperature, the same length of copper wire increases by 1.7×10^{-5} m. This implies that the same change in temperature on different materials of the same length produces different changes in length.

When you are interested to find the length L of the bar at the final temperature T, we use

$$L = L_0 + \Delta L = L_0 (1 + \alpha \Delta T)$$

Table 1 Linear expansion coefficients of some solids

Substance	linear expansion coefficient $(\times 10^{-5} K^{-1})$
Aluminium	2.7
Copper	1.7
brass	1.9
Iron	1.1
Concrete	1.2

Examples

The length of a steel wire at 20 ^{0}C is 2m. To what temperature should it be heated so that its length is increased by 0.1 cm?

Solution: $T_0 = 20\ ^0C$, $L_0 = 2m$, $\Delta L = 0.1\ cm = 10^{-3} m$

The length of the wire after it is heated,

$L = L_0 + \Delta L = 2m + 10^{-3}m$

$L = 2.001$ m

The rise in temperature can be derived from $\Delta L = \alpha L_0 \Delta T$ to be

$$\Delta T = \frac{\Delta L}{\alpha L_0} = \frac{10^{-3}\,m}{1.1\times10^{-5}K^{-1}\times2.00m} = 45.45\ K$$

The temperature of the wire after it is heated,

$T = T_0 + \Delta T = 10\ ^0C + 45.45\ ^0C$

$T = 55.45\ ^0C$

Examples

A steel bridge is built in several segments, each 20 m long. The bridge was constructed when the temperature was 20 0C. If a gap of 4 cm is left between neighboring segments what would be the maximum temperature that the bridge can manage before buckling?

Solution: $T_0 = 20\ ^0C$, $L_0 = 20.0$ m, $\Delta L = 4$ cm $= 4\times10^{-2}$m

The gap is filled from the two sides. You will find the temperature at which the gap can be filled. That is, the expected rise in temperature is

$$\Delta T = \frac{\Delta L}{\alpha L_0} = \frac{4.0\times10^{-2}m}{1.1\times10^{-5}K^{-1}\times20.0m}$$

$\Delta T = 180$ K

The temperature at which the bridge may buckle is

$T = T_0 + \Delta T = 20\ ^0C + 180\ ^0C$

$T = 200\ ^0C$

Surface (Area) expansion

So far we have seen expansion of objects only in one direction. Practically, this method is applicable for objects whose width and thickness of the object are very small compared to its length. Now what if only the thickness of the object is very small compared to its length and width? In this case, we will deal with thermal expansion in two dimensions:-surface expansion.

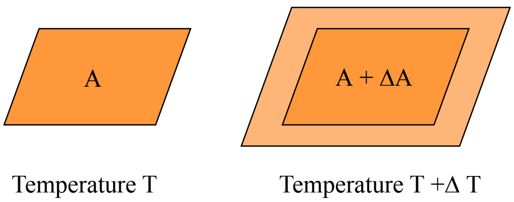


Figure 8. Area expansion of solids

Consider the plate of surface area A_0 at a temperature T_0, as shown in Figure 8. If the plate is heated until the temperature is increased by, ΔT, it expands in width and height such that the surface area is changed by ΔA. This change in area is directly proportional to the product of the original area and the change in temperature. Thus,

$$\Delta A = \beta A_0 \Delta T$$

where the proportionality constant β is called the coefficient of surface (area) expansion, and it can be measured by the unit $°C^{-1}$, or K^{-1}.

If the final surface area at the new temperature, T, is A, then $\Delta A = A - A_0$. After some substitutions and rearrangements, we have

$$A = A_0(1+\beta\Delta T)$$

Relationship between α and β

Suppose a square plate of side length, L_o and surface area, A_o, is experienced a change in temperature of ΔT, then the new area in terms of the new length L becomes

$$A = L^2 = L_o^2(1+\alpha\Delta T)^2 = A_o(1+2\alpha\Delta T+\alpha^2\Delta T^2)$$

Since α is to the order of 10^{-5}, then α^2 becomes to the order of 10^{-10}, and ignoring the third factor doesn't affect the result. Therefore, we can rewrite the formula as

$$A = A_o(1+2\alpha\Delta T)$$

Comparing this with equation $A = A_0(1+\beta\Delta T)$, we find that

$$\beta = 2\alpha$$

This is a very good approximation, so we do not need table of values for β as we can easily find it by doubling the value of α.

Examples

The surface area of one side of a circular brass plate at temperature 100 °C, is 3850 cm^2. To put this plate inside a cylinder, you need to cool it to 0 °C. What is the base area of the cylinder?

Solution: $T_0 = 100\ ^0C$, $T = 0\ ^0C$, $A_0 = 3850\ cm^2$

The area of the plate at T = 0°C is

$$A = A_0(1+2\alpha\Delta T)$$

$$A = (3850\ cm^2)\left[1+2\times(1.9\times10^{-5}K^{-1})(-100^0C)\right]$$

$$A = 3835.37\ cm^2$$

In order for the plate to pass into the cylinder, either side of its surface area should be reduced to below $3835.37\ cm^2$

Volume expansion of solids

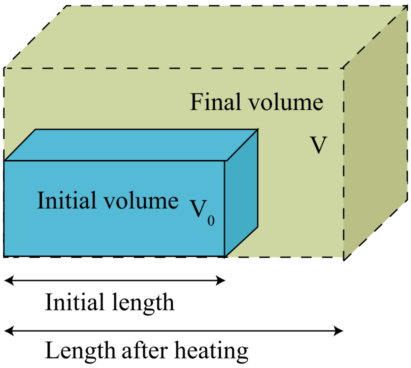


Figure 9. Volume expansion

When the length, the width and the thickness are equally significant, as shown in Figure 9, we need to consider the expansion of the solid in three dimensions. In this case, all the three lengths experience significant changes in length with a change in temperature ΔT.

The change in volume ΔV of an object subjected to a temperature change ΔT is given by

$$\Delta V = \gamma V_c \Delta T$$

Using $\Delta V = V - V_0$ and passing through some rearrangements, we have

$$V = V_0\left(1+\gamma\Delta T\right)$$

where V_0 and V are original and final volumes, respectively; γ is the coefficient of volume expansion of the block.

Relationship of γ to α and β

Suppose the side length of a cube of original length L_0 is increased to L when its temperature is increased by ΔT. Then, the volume of the cube after it is heated, is

$$V = L^3 = L_0^3\left(1+\alpha\Delta T\right)^3$$

Since $\left(1+\alpha\Delta T\right)^3 = \ +3\alpha\Delta T + 3\alpha^2\Delta T^2 + \alpha^3\Delta T^3 \approx 1+3\alpha\Delta T$, we can rewrite equation (10) as

$$V_c = V_c\left(1+3\alpha\Delta T\right)$$

Comparing equation (z) with this equation, we find that

$$\gamma = 3\alpha$$

Examples

A 200 liter aluminum cylindrical reservoir is filled with Ethyl alcohol $\left(\gamma = 112\times10^{-5}K^{-1}\right)$ at a temperature of 20 ^{0}C. what volume of alcohol will overflow if the system is heated to 100 °C ?

Solution:

$\alpha_{Al} = 2.31\times10^{-5}K^{-1}$, T_0 = 20 °C, T = 100 °C, V_0 =200 lit

The volume of the alcohol at 100 °C becomes

$$V_1 = V_0\left(1+\gamma\Delta T\right)$$

The volume of the cylinder at 100 ^{0}C is

$$V_{cy} = V_0\left(1+3\alpha_{Al}\Delta T\right)$$

The change in volume between the two substances at 100 oC will be

$$V = V_l - V_{cy} = V_0\Delta T\left(\gamma_l - 3\alpha_{Al}\right)$$

$$V = (200\text{lit})(80^0\text{C})(112\times10^{-5}\text{K}^{-1} - 3\times2.31\times10^{-5}\text{K}^{-1})$$

$$V = 16.81\text{lit}$$

Applications of thermal expansion in solids

1. Riveting metal sheets tightly

In this method, a hot steel rivet is used to join two metal sheets. The rivet is hammered whilst it is still hot to give a tight joint. As the rivet cools it contracts and makes the joint between the two metal sheets tighter, as shown in Figure 10.

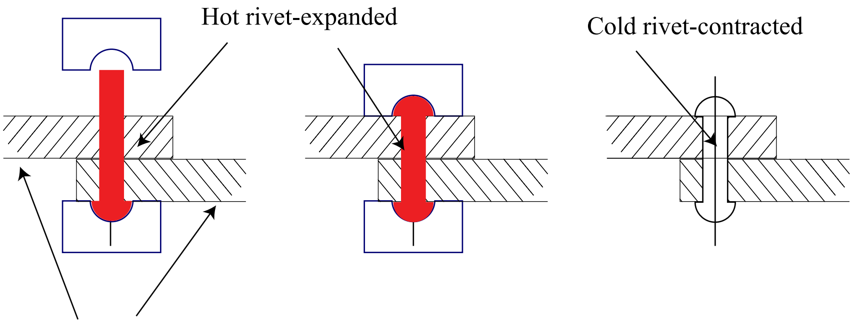


Figure 10. Riveting metal sheets tightly

2. The bimetallic strip

A bimetallic strip is made out of two metals of different coefficients of linear expansion bonded together. For example iron and brass bonded together. The coefficient of linear expansion (α) of iron (1.1×10^{-5} K^{-1}) is less than that of brass (1.9×10^{-5} K^{-1}). When the strip is heated, the brass expands faster than the iron and as a result the strip bends towards the iron side, as shown in Figure 11.

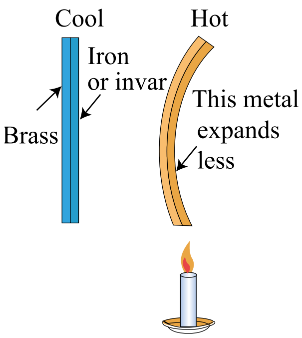


Figure 11. Bimetallic strip

A bimetallic strip can be used as a switch in an electric circuit that turns on and off according to the temperature. This switch is what we call thermostat.

Expansion of liquids

The force between particles in liquids is not as strong as that between particles in solids. As a result, for a given change in temperature liquids expand or contract faster than solids.

The formula used to calculate change in volume for a change in temperature of a solid can be applied for liquids. However, why we want to discuss volume expansion for liquids is that liquids are treated with their containers and consequently the expansion of the container affects the result for liquids.

While measuring the coefficient of cubic expansion of a liquid, the result is not a real value, rather it is an apparent value since the container itself is affected by the change in temperature. Therefore, the actual coefficient of volume expansion is given by

$$\gamma_r = \gamma_a + \gamma_c$$

where γ_r is the real value, γ_a is the apparent value and γ_c is the coefficient of cubic expansion of the container. Coefficient of volume expansion of some liquids are shown in Table 2

Table 2 Coefficient of volume expansion of liquids

Substance (Liquid)	Volume expansion coefficient (γ) $(\times 10^{-5} K^{-1})$
Petrol	95.0
Ethanol	75.0
Water	21.0
Mercury	18.0

The unusual behavior of water

The unusual behavior of water is an abnormal property of water whereby it expands instead of contracting when the temperature increases from 0 °C to 4 °C. The density of water has maximum value at 4 °C and decreases below this temperature, as shown in Figure 12. The density becomes less and less as it freezes. This is because molecules of water normally form open crystal structures when in solid form.

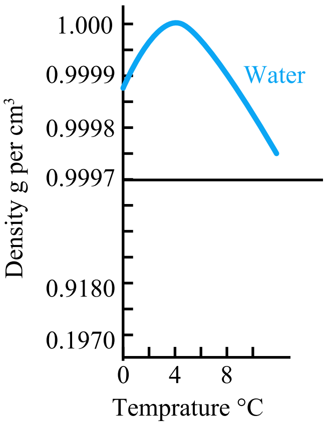


Figure 12. Density vs temperature graph for expansion of water

Most liquids change smoothly with increasing temperature. However, the expansion of water above 4

°C is not linear. The other important peculiarity of water is its coefficient of volume expansion varies with temperature.

Examples

Mercury of volume 10000 cm^3, which is filled in a brass container, is heated from 10 °C to 80 °C. What will be the real and apparent volume expansions of mercury in the brass container?

Solution: $T_0 = 10$ °C, $T = 80$ °C, $\gamma_{m,r} = 18\times10^{-5}K^{-1}$, $\gamma_b = 5.7\times10^{-5}K^{-1}$

The real expansion of mercury is

$$\Delta V_{m,r} = V_0\gamma_{m,r}\Delta T = \left(10^4 cm^3\right)\times\left(18\times10^{-5}K^{-1}\right)\left(80°C - 10°C\right)$$

$$\Delta V_{m,r} = 126\ cm^3$$

The apparent coefficient of volume expansion of mercury,

$$\gamma_{app} = 18\times10^{-5}K^{-1} - 5.7\times10^{-5}K^{-1} = 12.3\times10^{-5}K^{-1}$$

The apparent volume expansion of the mercury becomes

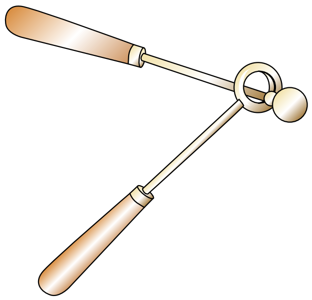
$$\Delta V_{app} = \gamma_{app}V_0\Delta T = \left(12.3\times10^{-5}K^{-1}\right)\left(10^4 cm^3\right)\left(70K\right)$$

$$\Delta V_{app} = 86.1cm^3$$

Do you see what a big difference is? This shows that we mercury will not be thermometric liquid in a brass capillary tube.

Exercises

1. A steel cork of a soft drink bottle at normal temperature is too tight to open it. Which method helps to open it easily; heating or cooling?
2. Does heating a thin, circular ring make it wider or narrower?
3. In the ball and ring experiment, the two metals are made of steel. At normal temperature; the ball can pass through the ring.
   (a) Which metal should be heated keeping the other at the initial temperature so that the ball cannot pass through the ring?
   (b) Which metal should be cooled keeping the other at the initial temperature so that the ball cannot pass through the ring?



4. The diameter of a piston is 20 cm. To what temperature should a steel ring of diameter 19.9 cm be heated so that the piston can pass through the ring?

5. What is the apparent coefficient of volume expansion of mercury in glass thermometer?
6. Calculate the increase in the volume of a sample of Ethyl alcohol of volume 008L and at 10 °C, when it is heated to a temperature of 50 °C

Upon completion of this topic you will be able to:

- demonstrate Charles, Boyle's, combined gas laws.
- some applications of the gas laws

This section deals with gas laws, which are applicable for ideal gases only. An ideal gas is a theoretical gas composed of many randomly moving point particles that are not subject to inter-particle interactions. An ideal gas establishes a relationship among the different gas variables such as pressure (P), Volume (V), and Temperature (T). The average kinetic energy of the gas-particle is directly proportional to the absolute temperature. In this section, you will learn laws that govern these phenomena, namely, Boyle's law, Charles' law, the pressure law and the combined gas law. These laws will be demonstrated using disposable syringes.

Ideal gas

An ideal gas has the following assumptions.

- In straight line, have constant and random speed.
- Made up of very large number of the same particles, very small compared to the space between them and perfectly hard spheres.
- There is no force between the particles. Particles but only collide elastically with the walls of the container and with each other.

Boyle's law

Boyle's law states that when the gas is kept at a constant temperature, its pressure P is inversely proportional to its volume V, thus,

$$P \alpha \frac{1}{V}$$

Hence, we have

$$PV = \text{constant}$$

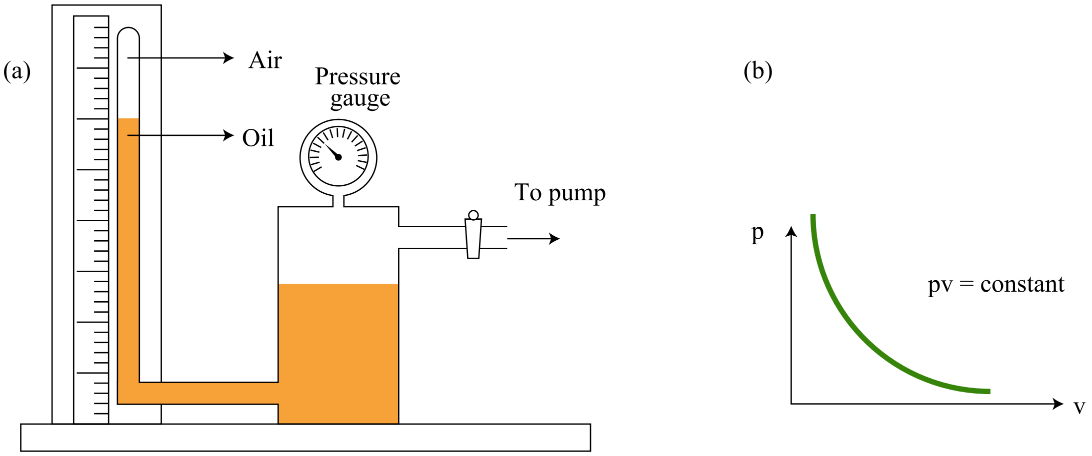


Figure 13. Boyle's law. (a) Gas is trapped in a glass tube by light oil. Pressure is exerted on the oil by a pump, to compresses the gas. (b) Pressure vs volume graph

From Figure 13, when the pressure changes from P_1 to P_2, the volume also changes from V_1 to V_2 , but their product remains constant. Thus,

$$P_1V_1 = P_2V_2$$

$$\text{or,} \quad \frac{P_1}{P_2} = \frac{V_2}{V_1}$$

Examples

The volume of a sample of gas, measured at 2.8 atm, is 18.20 mL. What will be the volume if the pressure becomes 2.00 atm, with a fixed amount of gas and temperature?

Solution:

Solving with the help of Boyle's law equation

$$P_1V_1 = P_2V_2, \text{ or } V_2 = \frac{P_1V_1}{P_2}$$

$$V_2 = \frac{2.8\text{atm} \times 18.20\text{mL}}{1.8\text{atm}}$$

$$V_2 = 28.31 \text{ mL}$$

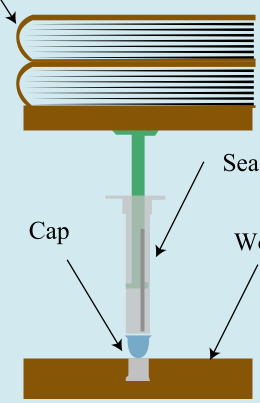
Activity 4

Verifying Boyle's law using sealed syringe

The objective of this activity is to verify Boyle's law and to plot the pressure-volume graph.

- To reduce friction, take the syringe and paste a thin layer of the lubricant to its rubber gasket with the help of a wooden split or tongue depressor.

- Your disposable syringe is 140 mL in volume. Pull the plunger of the syringe upwards up to around 110 mL.
- Attach the seal cap to the syringe in such a way that no leakage takes place. Arrange the system as shown in the figure.
- Measure the initial volume reading of the syringe.
- Place a wood block on the wooden piece and record the volume reading, Repeat this for two wood blocks, three wood blocks, four wood blocks, and five wood blocks. You can use wood blocks or other masses that can be comfortably placed on the wood block
- Remove all the books and weigh each. Also, weigh the wooden block with the plunger; it will give w_0.



- Reset the apparatus. Repeat all the above steps twice. Take the average of all the three activities.

PRECAUTIONS

- Proper lubrication is necessary to eliminate friction.
- The end of the syringe should be tightly fixed by a sealed cap so that the experiment will not fail.
- The syringe must be properly and firmly fixed, so that it can firmly withstand the weights.

Measurement

Measure the different volumes of interior air (V_i) by adding different weights. Record your observation using the observation table shown in Table 4.3.

Observation table

No	No. of books	Volume reading in mL (V_i)	Average (V_i)	Weight in g (w_i)	Total weight in g
1					
2					

No	No. of books	Volume reading in mL (V_i)	Average (V_i)	Weight in g (w_i)	Total weight in g
3					
4					
5					

Calculation and plotting:

The pressure exerted on the air inside the syringe is equal to the pressure exerted by the weights plus atmospheric pressure (P_{atm} = 101.325 kPa).

The pressure exerted by the weights inside the syringe is equal to the force exerted by the weights divided by the interior cross-sectional area of the syringe.

Use the calculation table shown in Table 4.4. Then, plot the graph of P_i vs V_i and P_iV_i vs V_i.

Calculation table

No. of books	P_w in kPa	P_i in kPa	V_i in mL	P_iV_i
0				
1				
2				
3				
4				

Questions:

1. Do your graphs verify Boyle's law?
2. What were the major challenges during your activity?

Expected results

- Boyle's law is verified if the graph shows that is a straight line.

Charles' law

Charles' law states that when the pressure is kept constant, the volume V of the gas is directly proportional to its absolute temperature, as

$V \alpha T$ .from this, we have

$$\frac{V}{T} = \text{constant}$$

When the temperature changes from T_1 to T_2, the volume also changes V_1 to V_2, but their product remains constant. Thus,

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

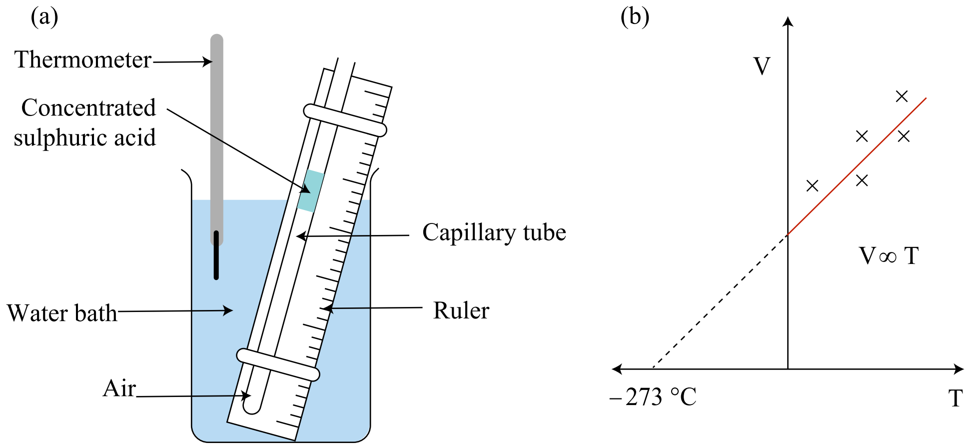


Figure 14. Charles' law. (a) Gas is trapped in a capillary tube by a bead of concentrated sulphuric acid, since gas column is dry. The gas is heated in a water bath, and the volume measured by the length of the column. (b) V vs T graph

If the temperature is somewhat above the condensation point and the pressure is constant, the volume is linearly proportional to the temperature. The absolute zero can be determined by extrapolation to be –273.15°C, as shown in Figure 14.

Activity 5

In Figure 14, absolute temperature is obtained at zero volume. Is it possible for a volume to be zero? If not what is the physical meaning of this result?

Examples

A sample of Carbon dioxide in a pump has a volume of 20.0 mL at 40.0 °C. If the amount of gas and pressure remain constant, to what amount would the temperature be raised so that the volume would increase to 24.0 mL°C?

Solution: $V_1 = 20.0$ mL, $V_2 = 24.0$ mL, $T_1 = 40.0$ °C= 313.0 K

From Charles' law, we have

$$T_2 = \frac{V_2}{V_1} T_1 = \left(\frac{24.0 \text{ mL}}{20.0 \text{ mL}}\right)(313.0\text{K})$$

$$T_2 = 375.6\text{K}$$

Activity 6

In this experiment, you will verify Charles's law by studying a change of the total volume of the air in a conical flask as the flask moves through various solutions, and you will estimate the absolute zero temperature from volume-temperature graph.

- Prepare the four solutions using the four equal beakers as follows:

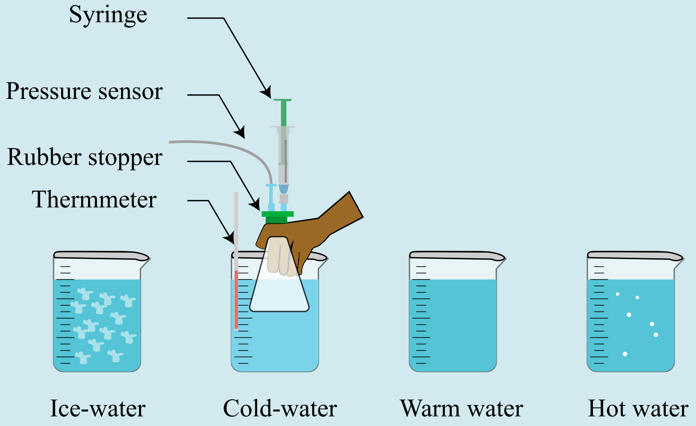
  Ice-water: Ice, salt, and a small amount of tap water

  Cold water: 50 % Ice and 50 % tap water

  Warm water: Slightly heat tap water using a heating plate.

  Hot water: Heat tap water until the temperature reaches around 40 °C to 50 °C.
- Take a conical flask that can be easily submerged in a beaker and attach its rubber stopper.
- A syringe and a pressure sensor (barometer) should be already fixed to the rubber stopper. The rubber stopper should be tightly attached to the flask to keep the inside air isolated.
- Immerse the flask in the ice-water beaker. Since the flask is denser than the air, it will float on the water surface. So we have to hold the immersed flask inside the beaker.
- Complete other activities.

The figure below shows the experimental diagram to verify Charles's law.



Precautions

- The rubber stopper should be tightly fixed on the flask to entrap the air.
- The temperature and the volume readings are recorded at a steady pressure.
- Use safety gloves when dealing with hot surfaces.
- The flask should be properly immersed in the beaker, so that the temperature of the air reaches the temperature of a solution.

Recording observation, Calculation and Plotting

- The total volume of the air is the volume of the flask plus the volume reading from the syringe.
- Convert the temperature (in °C) to the Kelvin (in K).
- List the volume to temperature ratios in the Table 3.
- Draw the graphs of volume vs temperature

Table 3 Recording and calculation table

Temperature T (in°C)	Temperature T (in K)	Volume of syringe V_S (mL)	Volume of flask V_f (mL)	Total Volume V (mL)	V(mL)/ T(K)

Exercises

Questions:

1. Does your result meet Charles' law?
2. What is the ratio of volume to temperature?
3. Is your graph linear? If that is so, determine the slope.
4. Extrapolate your graph to get the absolute zero temperature. What is your value?

Expected results:

1. The volume vs temperature is a straight line.

The pressure law or Gay-Lussac Law

According to this law, when the volume is constant, the pressure is directly proportional to the temperature

$$P \propto T$$

Therefore, you will also have

$$\frac{P}{T} = \text{constant}$$

or,

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

The pressure vs temperature graph is depicted as shown in Figure 15.

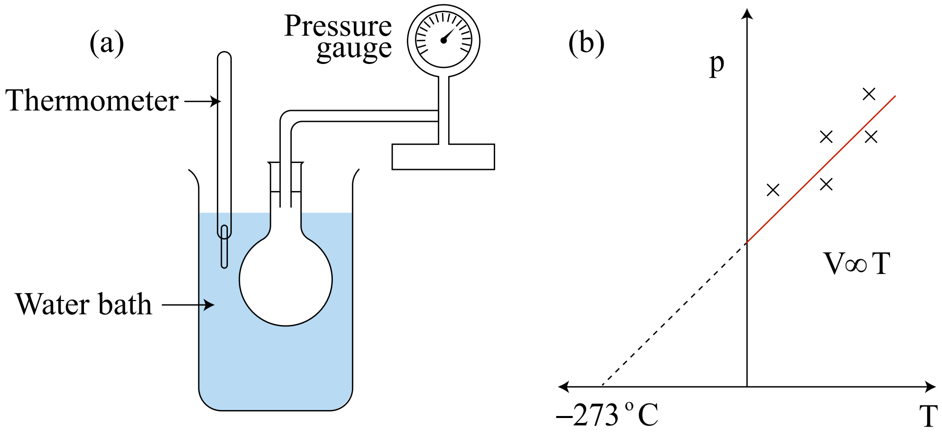


Figure 15. Pressure law. (a) Gas is trapped in a flask and heated in a water bath or an oil bath if a higher temperature is required. (b) Pressure vs temperature graph.

Examples

What will the change in pressure be when a gas at 2.50 atm is heated from 40.0 °C to 50.0 °C, while the volume of the gas kept constant?

Solution:

$P_1 = 2.50\,\text{atm}$, $T_1 = 40.0°\text{C} = 313.0\,\text{K}$, $T_2 = 50.0°\text{C} = 323.0\,\text{K}$

According to the Gay-Lussac law

$$P_2 = \left(\frac{T_2}{T_1}\right)P_1 = \left(\frac{323.0\,\text{K}}{313.0\,\text{K}}\right)(2.50\,\text{atm})$$

$P_2 = 2.58$ atm

The change in pressure is

$$\Delta P = P_2 - P_1 = 2.58\text{atm} - 2.50\,\text{atm} = 0.8\text{ atm}$$

Constant-Volume Gas thermometer – Thermometer calibration

A constant-volume gas thermometer depends only on the properties of an ideal gas. Since it doesn't change over a wide variety of temperatures, it is used to calibrate thermometers based on other materials. A constant-volume gas thermometer uses a gas-filled bulb of unknown temperature along with a mercury manometer, as shown in Figure 16.

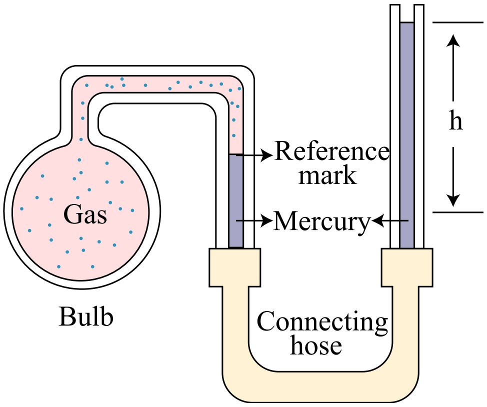


Figure 16. Device to calibrate thermometer

Constant-Volume Gas thermometer functions by the principle that the relationship between pressure and temperature in a system of an ideal gas is linear. Such a thermometer measures temperatures in the range from 0 K to 500 K.

Consider the P-V diagram in Figure 17.

- The pressure of water and ice is measured, that point is 0 °C.
- The pressure of water and steam are again measured while the volume is kept constant, that point is 100 °C.
- Then, connect the two points by a straight line.
- To find the temperature of the substance, first measure the pressure, then draw a perpendicular line from the pressure axis to meet the solid line, then drop a perpendicular line to the temperature axis, as shown in Figure 17. This is the temperature reading of the substance.

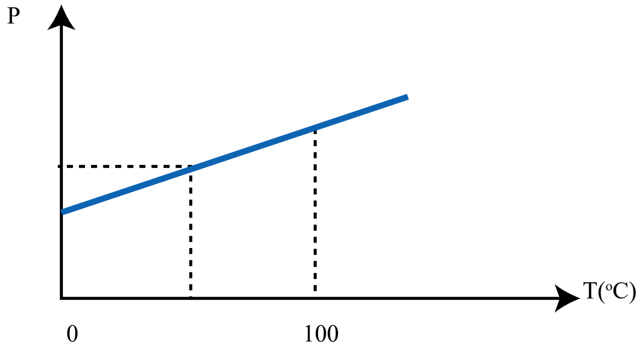


Figure 17. The P-T graph

If you extend the line in Figure 18 to the left, it touches the negative temperature axis at absolute zero or -273.15 °C, or 0 K. If you repeat this for different gases, you will have different slopes, but all of them touch absolute zero point, as shown in Figure 18. At absolute zero, the molecules no longer move. This can be used as one point of calibration.

If we also measure at the triple point (for reference), we get

$$T_3 = CP_3$$

Taking the ratio:

$$\frac{T}{T_3} = \frac{P}{P_3}$$

$$T = T_3\left(\frac{P}{P_3}\right) = 273.16\left(\frac{P}{P_3}\right)$$

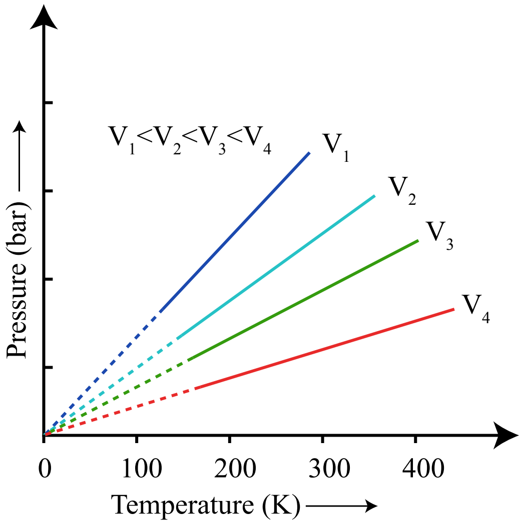


Figure 18. For different constant volumes, different P-T curves, but all converge to absolute zero.

Examples

The pressure of a gas at the triple point is 6.07 atm. What will be the temperature of the gas at 1 atm?

Solution: $P = 6.07$ atm

The desired temperature, T, is

$$T = 273.16\left(\frac{P}{P_3}\right) = (273.16\text{K})\left(\frac{1\text{atm}}{6.07\text{atm}}\right) = 45.0\text{ K}$$

The combined gas law

The general gas law is stated as, pressure, volume and temperature, are changing, then the product of pressure and volume is directly proportional to the temperature.

$$PV \propto T$$

$$\frac{PV}{T} = \text{constant}$$

or, $$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Examples

A gas has an initial pressure of 400 atm, a temperature of 50 K, and a volume of 300 mL. If the temperature is increased to 200 K and the pressure is decreased to 300 atm, what will be the new volume?

Solution: P_1 = 400 atm, P_2 = 300 atm , T_1 = 50 K, T_2 = 100 K, V_1 = 300 mL, V_2 = ?

Using the combined gas law,

$$V_2 = \left(\frac{P_1}{P_2}\right)\left(\frac{T_2}{T_1}\right)V_1$$

$$V_2 = \left(\frac{400\ \text{atm}}{300\ \text{atm}}\right)\left(\frac{100\ \text{K}}{50\ \text{K}}\right)\times 300\ \text{mL}$$

$$V_2 = 800\,\text{mL}$$

Exercises

1. Which law compares gases at two different sets of conditions, with temperature as a constant and pressure and volume as variables?
2. How does the pressure exerted by the gas change when the volume of confined gas decreases?
3. How can you increase the pressure of a gas keeping the temperature constant?
4. Each of the plastic bottles, as shown in the figure below, contains the same number of gas molecules. In which bottle is the pressure highest?

Bottle 1 Bottle 2 Bottle 3 Bottle 4

5. A sample of gas occupies 5.4 liters at a temperature of 24°C. At what temperature will the gas occupy 10.0 liters when the pressure is constant?
6. The volume of a nitrogen gas is 1000 ml at a pressure of 0.8 atm and at constant temperature. What volume will the gas fill if the pressure doubles?
7. When a supply of hydrogen gas is held in a 4-liter container at 300 K, it exerts a pressure of 0.8 atm. The supply is moved to a 1.5-liter container and cooled to 150 K. What will be the new pressure of the confined gas?

SUMMARY

- Heat is defined as a form of energy in transit due to temperature differences. it is therefore measured in joules (J).
- The temperature of a substance is a measure of the average kinetic energy of the particles within the substance. Temperature is a fundamental physical quantity whose SI unit is Kelvin (K).
- Two objects are said to be in thermal equilibrium if they have the same temperatures. Two objects in thermal equilibrium do not exchange heat energy.
- The most commonly known scales which scientists now tend to deal with are the Kelvin scale (K), the Celsius scale (°C) and the Fahrenheit scale (°F).
- Thermometry is the process of measuring temperature of substances. The instrument that is used to measure temperature is known as Thermometer.
- Anybody with at least one measurable property that changes with temperature can be used as thermometer. Such a property is called thermometric property.
- The particular substance that exhibits changes in the thermometric property is known as thermometric substance.
- One of the effects of heating is thermal expansion. Substances expand when they absorb heat and contract when they release heat. Thermal expansion or contraction occurs spherically in all dimensions but it can be broken down into three categories: Linear expansion, surface (area) expansion and volume expansion.
- The change in length ΔL of a substance, attained by heating, is directly proportional to the product of the original length L_o, and the change in temperature ΔT. Thus, $\Delta L = \alpha L_0 \Delta T$, where the proportionality constant α is called the coefficient of linear expansion.
- The change in area of a substance is $\Delta A = \beta A_0 \Delta T$, where the proportionality constant β is called the coefficient of area expansion.
- The change in volume of a substance is $\Delta V = \gamma V_0 \Delta T$, where the proportionality constant γ is called the coefficient of volume expansion.
- The coefficients of expansion constants are related as $\gamma = 3\alpha,\ \beta = 2\alpha.$.
- Boyle's law states that when the gas is kept at a constant temperature, its pressure P is inversely proportional to its volume, $P \alpha \frac{1}{V} \Rightarrow PV = \text{cons tan t}.$
- Charles' law states that when the pressure is kept constant, the volume of the gas is directly proportional to its temperature, $P \alpha T \Rightarrow \frac{V}{T} = \text{constant}.$

- According to the pressure law, when the volume is constant, the pressure is directly proportional to the temperature, $P \alpha T \Rightarrow \frac{P}{T} = \text{constant.}$
- The general gas law can be described as when all the three parameters are changing, then the product of pressure and volume is directly proportional to the temperature.

$$P \alpha T \Rightarrow \frac{P}{T} = \text{constant.}$$

Exercises

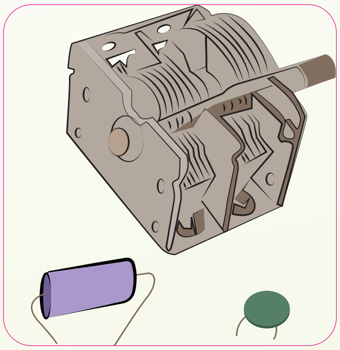
1. A molecule of protium (an isotope of hydrogen) has atomic weight 1; helium atom has atm. wt 4; and oxygen molecule has atm. wt 32. At the same pressure and temprature which molecule has
   (a) The smallest average kinetic energy?
   (b) The slowest and which one has the fastest speed?
2. What do you think the reason why there is very little helium in the atmosphere?
3. During phase change, no temperature rise is observed. What happened to the heat supplied to the object?
4. Although Earth is not in physical contact with the sun, it receives heat energy from the sun. Why don't they come to thermal equilibrium?
5. In liquid in glass thermometer, what would be the reading of the thermometer since the glass itself undergoes thermal expansion?
6. Gases do not have volume expansion coefficients. Why?
7. Does adding heat to a substance always increase its temperature?
8. Write two conditions where heat enters into an object.
9. Explain what would happen to the temperature and heat flow between to objects, which were at different temperatures, are brought in thermal contact?
10. What will be the increase in length of an iron pipeline that is 40 m long at 10 °C when it is heated to 50 °C?
11. Calculate the increase in volume of water that has a volume of 4.5×10^{-4} m^3 at 20 °C when it is heated to 50 °C.
12. Explain why the apparent thermal expansion of mercury in a glass tube is less than the real thermal expansion.
13. A gas has an initial pressure of 70 mm Hg, a volume of 60 mL and a temperature of 180 K. The pressure was then increased to 140 mm Hg, and the volume is 40 mL. What is the new temperature?

P10CH05

CHAPTER 5

ELECTROSTATICS

Chapter Contents



Chapter Outcomes

You will be able to recognize:

- an electric charge produces an electric field;
- the methods of detecting an electric charge;
- the importance of capacitors in electrical and electronic devices.

Introduction

It is common experience for most of you to see a spark or to hear a crackle when you take off our synthetic jackets or sport shirt, particularly during dry weathers. You may also experience shocking sensation while touching some metal surfaces. Have you ever tried to find any cultural or scientific reason for these phenomena? Another common observation for most of us is lightning that we see in the sky during thunderstorms. The reason for all these phenomena is discharge of electric charges, which were accumulated due to friction. In other words, such a phenomenon is due to generation of static electricity. This is precisely the topic we are going to discuss in this unit. Static means anything that does not move or change with time, and static charge is charge at rest. Electrostatics deals with the study of forces, fields and potentials arising from static charges.

Upon completion of this topic you will be able to:

- identify the two kinds of electric charges.
- distinguish between conductors and insulators.

The credit of the discovery of the fact that amber rubbed with wool or silk cloth attracts light objects is given to ancient Greeks, around 600 BC. The name electricity is taken from the Greek word "elektron" meaning amber. Now days, the process of electrification is very common experience. This section deals with the concept of charges and methods of electrification.

KEY TERMS

- **Electrification** is the process of imparting extra positive or negative charge to a body

What is electric charge?

All ideas of electricity are based on the theory that all pieces of matter are made from atoms. An atom is the smallest unit of matter, which consists of three fundamental particles known as electrons, protons and neutrons. A series of experiments showed that electrons and protons possess a property called electric charge. It was also revealed that there are two kinds of charges; the negative charge and the positive charge. The negative charge is carried by electrons and the positive charge is carried by protons. It was also known that neutrons are charge free particles, and are called electrically neutral.

The SI unit of electric charge is coulomb (C); where $1\ C = 6.25\times10^{18}$ electrons. An electron and a proton carry the smallest indivisible charge. The magnitude of the charge, carried by a proton or an electron, is the ultimate natural unit of charge whose magnitude (e) is

$$e = 1.6 \times 10^{-19}\ C$$

The total charge carried by N number of electrons or protons can be expressed in terms of this elementary charge as

$$Q = \pm Ne$$

Using this equation, you can easily find that 1 C of charge is carried by approximately 6.25×10^{18} electrons or protons.

An electrically neutral atom carries equal number of electrons and protons. An atom can be charged either positively or negatively by losing or gaining electrons, respectively. In macroscopic level, an object is electrically neutral if the number of electrons in it is equal to the number of protons. An object becomes positively or negatively charged if it loses or gains electrons, respectively.

Examples

A charged metal sphere carries a total charge of -3.2×10^{-7} C. How many extra electrons are there in the metal sphere?

Solution: $Q = -3.2\times10^{-7}$ C

Each electron carries the elementary charge $e = 1.6\times10^{-19}$ C. Therefore, the total charge Q is related to the elementary charge, e and the number of electrons, N, by Q = Ne. From this, we find

$$N = \frac{Q}{e} = \frac{-3.2\times10^{-7}\,C}{-1.6\times10^{-19}\,C} = 2\times10^{12}$$

That is, a charge of $-3.2\times10^{-7}\,c = -0.32\mu c$ is carried by 2×10^{12} electrons.

Conductors and insulators

If you connect an electrically neutral pith ball and a glass rod by a copper wire, you will find that the neutral pith ball has been charged similarly with the glass rod. This shows that charge has been imparted to the pith ball through the copper wire. Such materials like copper, aluminum, etc., which permit the flow of charge through them are called conductors of electric current.

On the other hand, if you connect the charged glass rod by a neutral nylon cord instead of copper wire, you will find the neutral pith ball will not be charged.

Materials like the nylon cord that do not allow the flow of electric current through them are called insulators.

Charge carries in conductor

- In solid conductors, charge carriers are electrons.
- In semi-conductors, charge carriers are holes and electrons.
- In electrolytes, charge carriers are ions (positive and negative ions).

If charge is transferred to a conductor, it distributes over the entire surface of the conductor. Extra charge cannot exist inside a conductor, rather, resides on the surface. In contrast, if charge is put at a place on an insulator, it stays at that same place.

When we connect a charged body with the ground, all the excess charge on the charged body disappears by flowing to the ground through the connecting conductor. This process of sharing the charges with the earth is called grounding or Earthing. Earthing provides a safety measure for electrical circuits and appliances by transferring extra charge from circuits to the ground.

Metals in general are good conductors of electricity, while most nonmetals are insulators. This is because; unlike that of insulators, a few outer electrons within metals become detached from each atom and can move freely throughout the metal. These free electrons are often spoken of as an electron cloud. The electron cloud helps the flow of charge through metals.

Charging methods

Most objects in our surrounding are electrically neutral. Actually, there is a possibility that many substances can be electrified by rubbing (friction), by sharing (conduction) and by induction. Next, you will learn these charging techniques.

A. Charging by Rubbing

When two different objects are rubbed against each other, their temperatures rise due to the friction. In this case, the outermost shell electrons of the atoms of the more electropositive material, gain enough kinetic energy that enables them to escape from their parent atoms. The escaped electrons will jump to the other interacting object leaving the first positively charged and making the second one negatively charged. Consider the following example.

When a rubber rod is rubbed with animal fur, the electrons from the animal fur will transfer to the rod and as a result the rubber rod becomes negatively charged.

Thus, by rubbing, objects are charged oppositely.

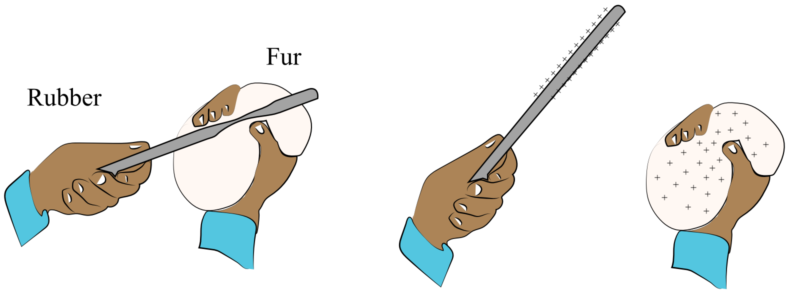


Figure 1. By rubbing or friction, bodies are charged oppositely

B. Charging by sharing or conduction.

If a metal conductor is touched by a charged rod, the charge of the rod is shared out over the conductor. In Figure 2, when a metal sheet is touched by the charged plastic rod, extra electrons of the rod will be shared to the metal keeping both the rod and the metal conductor negatively charged.

By sharing, or touching bodies are charged similarly.

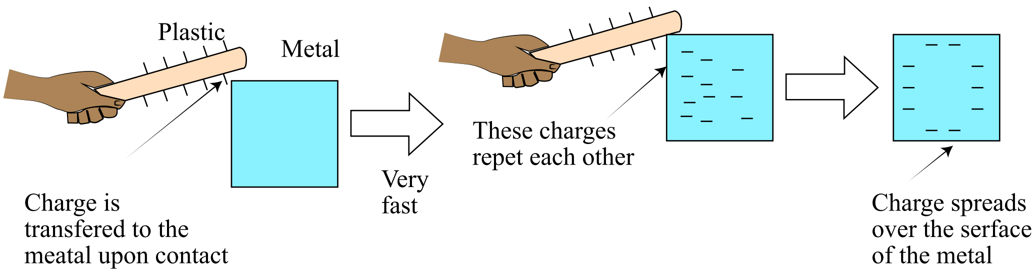


Figure 2 Charging by touching or sharing

C. Charging by induction

Charging by induction takes place without physically contacting the objects. When a negatively charged rod is brought close to a neutral metal sphere, as shown in Figure 3, the negative charge in the rod pushes conduction/free electrons on the surface of the metal towards the opposite side, leaving the left side positively charged. When the right side of the metal is connected to the ground by a conducting wire, electrons pushed by the negative rod will flow down the wire. Finally, remove the conducting wire before removing the rod and then you will find the metal sphere charged positively.

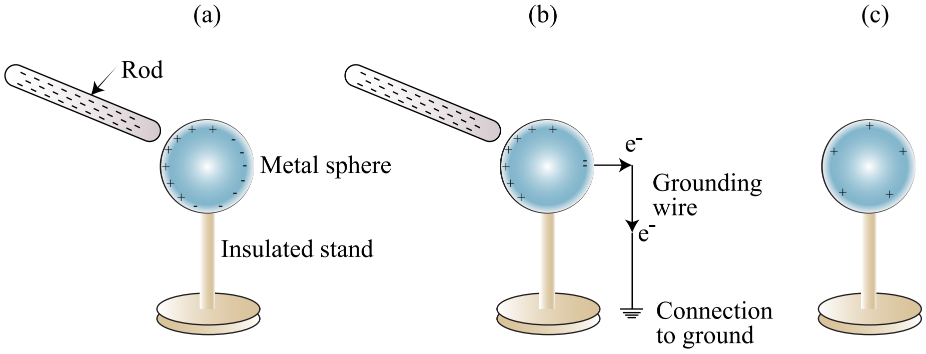


Figure 3. Charging a metal sphere by induction

Similarly, if the same metal sphere is approached by a positively charged rod, free electrons from the metal sphere are attracted towards the rod leaving the opposite side positively charged. If the opposite side is grounded, electrons from the ground will enter into the sphere. Remove the connecting wire before removing the rod. Then you will find that the metal sphere will be charged negatively.

Thus, by induction, bodies are charged oppositely.

You have learnt that certainly one fundamental property of electric charge is its existence in the two varieties that were long ago named positive and negative. The observed fact is that all charged particles can be divided into two classes such that all members of one class repel each other, while attracting members of the other class. If two small electrically charged bodies, A and B, some distance apart, attract one another, and if A attracts some third electrified body C, then we always find that B repels C.

Thus, electrostatic phenomena arise from the forces that electric charges exert on each other. The interaction between the two types of charges is governed by the basic laws of electrostatics, which are defined as Like charges repel each other and unlike charges attract each other.

Gold leaf electroscope

A gold leaf electroscope is a sensitive type of electroscope that consists of two gold leaves. It consists of a brass rod with a brass disk at the top and at the bottom, there are two thin gold leaves in the form of foils. In order to keep the rod in place, the rod travels through the insulator. The charges move from the disk to the leaves through the rod. At the lower portion of the jar, a thin aluminium foil is connected.

The aluminium foil is grounded with the help of a copper wire so that the leaves are protected from external electrical disruptions. Figure 4 shows the structure of a simple gold-leaf electroscope.

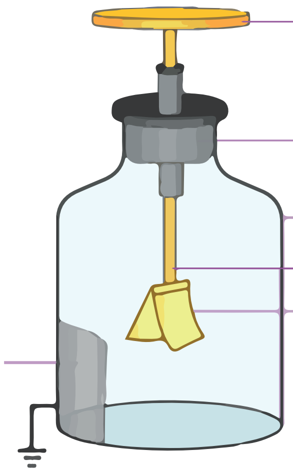


Figure 4.

Applications of gold leaf electroscope

The gold-leaf electroscope is used to detect charge, identification of the nature of the charge, and identification of body as a conductor or an insulator.

(i) Detection of charge

For the detection of charge, the object that needs to be tested is touched with the metal cap. If the leaves diverge, the body is said to be charged and if there is no change in the leaves of the electroscope, then the body is uncharged.

(ii) Identification of the Nature of the Charge

Suppose a positively charged body is brought near the metal cap and an unknown body is brought near the metal cap. If the leaves diverge further, we can conclude that the unknown body has a positive charge. If the leaves come closer to each other, then the charge of the unknown body is negative.

(iii) Identification of Body as a Conductor or an Insulator

To identify if a body is a conductor or an insulator, two gold leaf electroscopes are taken. One gold leaf electroscope is charged so that the leaves will diverge. Then the other gold leaf electroscope is connected to the first one. If the leaves of the other electroscope diverge, then the body is said to be a conductor and if there is no change in the leaves, the body is said to be an insulator.

Exercises

1. Why is a gold leaf electroscope enclosed in a glass case?
2. What does the degree of divergence of gold leaves mean in a gold leaf electroscope?
3. Why do the gold leaves in an electroscope fold back when touched with hands?

Activity 1

The objective of this demonstration is to examine electrification using silk and glass rod.

(a) Suspend 2 pith balls side by side using insulating strings
(b) Rub the piece of silk cloth with the glass rod
(c) Touch the two suspended pith balls with the glass rod

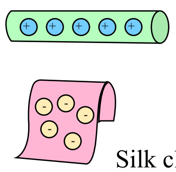
Questions

1. Do the two pith balls attract or repel each other?
   (a) Replace each of the two pith balls by other neutral pith balls.
   (b) Rub the piece of silk cloth with the glass rod.
   (c) Rap one pith ball for a sufficient time with the rubbed piece of silk cloth. Touch the other pith ball with the rubbed glass rod.
2. What do you observe after the charged silk and glass rod are removed from the pith balls? Do they repel or attract each other?

Exercises

1. Every piece of matter contains very large number of charged particles: electrons and protons. However, most objects in our surrounding are electrically neutral. Why?
2. An inflated charged pith ball is suspended in air by a plastic cord. Is it in wet air or dry air that the pith ball loses its charge quickly? Why?
3. Is it possible to charge two identical plastic rods by rubbing one with the other? Give reason.
4. A positively charged metal sphere can be discharged by connecting it to the ground by a conducting wire. What was going on during the discharging process?
   (a) Extra positive charge is carried to the ground by protons.
   (b) Electrons flow to the metal sphere to neutralize extra positive charge in the sphere.
5. Two electrically neutral spheres, one copper and the other plastic, are suspended by insulating strings. How does charge redistribute in each sphere if each of these spheres is touched by a charged glass?
6. A charged object does not interact with an electrically neutral object. So, why does a plastic comb that has been rubbed with air attract small pieces of electrically uncharged paper?

7. It is common to see that if a plastic object and a metal object are placed near each other, the plastic object is covered with much dust than the metal object. What can it be the reason related to static electricity?
8. Devices made to store electric charge, are made of metals not insulators. Why?
9. Write some uses and hazards of static charges.
10. Write some antistatic devices.
11. In the figure shown at the right, a piece of cloth and a glass rod are rubbed against each other, and are charge oppositely. If you connect them by a conducting wire
    (a) Do they get naturalized? why?
    (b) Would they get naturalized if both objects were metals?



Upon completion of this topic you will be able to:

- State Coulomb's Laws of Electrostatics
- Solve problems on Coulomb's Law

So far, you have learnt how electric charges interact with each other. However, the basic law of electrostatic doesn't tell us how much force can two given charges exert on each other. Next, you will learn how to find the magnitude and direction of electrostatic forces.

KEY TERMS

- Point charges are charges carried by objects whose dimensions are very small compared to their separation distance.

Electrostatic force- Coulomb's law

If two point charges are brought near each other, each of them exerts a force on the other. Thus, the two charges exchange equal and opposite forces. The force between the two charges is an "action-at a-distance" force. It can act across empty space and does not need any matter in the intervening space to transmit the force. This interaction force can be quantified by Coulomb's law. Coulomb law clearly defines how the interaction force can be determined. Coulomb's law is defined as follows:

"The force of interaction of two electrostatic point charges in vacuum is directly proportional to the product of the two charges and inversely proportional to the square of their separation".

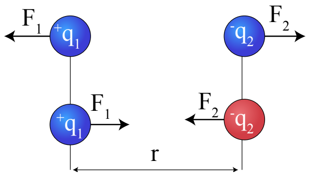


Figure 5. Force between point charges

Consider two point charges q_1 and q_2 which are at a distance r apart, as shown in Figure 5. Then, the magnitude of the electrostatic force between the two charges is given by Coulomb law as

$$F = k\frac{|q_1||q_2|}{r^2} = \frac{1}{4\pi\varepsilon_0}\frac{|q_1||q_2|}{r^2}$$

where

- Coulomb's constant (k) and permittivity of vacuum (ε_0), are related by $K = 1/4\pi\varepsilon_0$
- $k = 9\times10^9\,\text{Nm}^2/\text{C}^2$ and $\varepsilon_0 = 8.84\times10^{-12}\,\text{C}^2/\text{Nm}^2$

We can easily understand that the two charges experience action-reaction force pairs $F = \left|\vec{F}_1\right| = \left|\vec{F}_2\right|$. Whether attractive or repulsive, the line of action of these action-reaction force pairs lie on the line connecting the two point charges.

Examples

Two identical copper spheres carry +0.4 μC and −0.8 μC charges. They are separated by 20 cm and their size is very negligible compared to their separation distance. Assume between the two spheres is vacuum.

(a) What is the electrostatic force between the two spheres?

(b) Now suppose the two spheres are connected by a copper wire for sufficient time. What will be the force between them after the conductor is removed?

Solution

$q_1 = +0.4\ \mu\text{C}$, $q_2 = -0.8\ \mu\text{C} - 0.8\ \mu\text{C}$, r = 20 cm

First, let us convert the units into SI units.

$q_1 = +0.4\mu\text{C} = +0.4\times10^{-6}\,\text{C}$, $q_2 = -0.8\mu\text{C} = -0.8\times10^{-6}\,\text{C}$, r = 20 cm = 0.2 m

(a) The reason that we assumed the size of each sphere to be very small compared to their separation distance is to treat them as point charges. The force between the two spheres can be calculated from coulomb's law as

$$F = k\frac{|q_1||q_2|}{r^2} = \left(9\times10^9\,\text{Nm}^2/\text{C}^2\right)\frac{\left(0.4\times10^{-6}\,\text{C}\right)\left(0.8\times10^{-6}\,\text{C}\right)}{(0.2\ \text{m})^2}$$

F = 0.072 N, attractive force

(b) The reason why we connect the two spheres for sufficient time is to attain electrostatic equilibrium. Since the two spheres are identical in property and size, they share the total charge equally. Thus, Total net charge,

$$Q = q_1 + q_2 = +0.4\times10^{-6}C + \left(-0.8\times10^{-6}C\right) = -0.4\times10^{-6}C$$

The charge carried by each sphere after electrostatic equilibrium is

$$q = \frac{1}{2}Q = -0.2\times10^{-6}C$$

The new force between the spheres is not attractive, but it is repulsive. The magnitude of this repulsive force is

$$F = k\frac{|q||q|}{r^2} = \left(9\times10^9 Nm^2 / C^2\right)\frac{\left(0.2\times10^{-6}C\right)^2}{\left(0.2\ m\right)^2}$$

$$F = 9\times10^{-3} N$$

Exercises

1. The electric repulsion force between two equal, positive point charges is (Q) is F. Suppose the separation distance between the two charges is doubled.
   (a) What will be the force between these charges after their separation distance is doubled?
   (b) How much charge should be added only on one of the charges so that the force between them remains the same?
   (c) How much charge should be added on each charge Q to keep the force unchanged?
2. What is the force between two point charges, 4 C and 5 C, placed 0.5 meter apart in a vacuum?
3. According to Bohr's atomic model, an electron of a hydrogen atom revolves around one proton in the nucleus. What is the electric force between the proton and the electron? (Radius of the atom = 120 pm)

Upon completion of this topic you will be able to:

- illustrate lines of force relative to electric charges.
- solve problems on electric field intensity and work done in an electric field.

You might have learnt about action-at-a-distance forces. These forces are interactions without any actual physical contact between them. Electrostatic force is one of action-at-a-distance forces. When two charges are brought close to each other, they interact electrically. Therefore, there should be something between the two charges which is created by the charges themselves. This is called electric field, which is the focus of this section. Under this section, you will learn how to map electric fields, potential difference in an electric field, and work done on a charge placed in a uniform electric field.

Electric field

If a point positive charge "q" is placed near another positive source charge Q, it experiences a repulsion force. If we change the position of q without receding charge Q, the force still exists with the same or a different force depending on the separation distance between the two charges. The source charge Q is said to produce or cause an electric field at all other points in its vicinity. Thus, the two particles are interacting by the fields they produce due to their charges. Therefore, you can put any point charge at point P, and it experiences a force F, you can take the point of view that the force is exerted by the field, rather than directly by charge Q.

The experimental test for the existence of an electric field at any point is simply to put a test charge at the point. If a force of electrical origin is exerted on the test charge, placed at a point, then an electric field exists at the point.

Electric field is a region where electric forces act on charges when placed at any point in the region.

Electric lines of force

Electric field can be visualized as consisting of imaginary lines called electric lines of force. Each line corresponds to the path that a positive test charge would take if it is placed in the field on that line. That means, to determine the direction of the electric field at a point, we place a positive test charge at that point, then the direction of the field is determined to be in the direction of the force exerted on the test charge. Some properties of electric lines of force are discussed below.

Electric field lines have the following properties

- Electric field lines do not cross each other.
- Electric field lines are directed away from a positive charge and directed towards a negative charge, as shown in Figure 6.
- For an extended charged object, any line of force into or out of the object is drawn perpendicular from its surface.

- The density of field lines is directly proportional to the magnitude of the electric field strength. The field is strong when the lines are close together, and it is weak when the field lines are dispersed apart from each other.
- Lines of force from opposite charges connect, but that of similar charges do not connect, as shown in Figure 7.

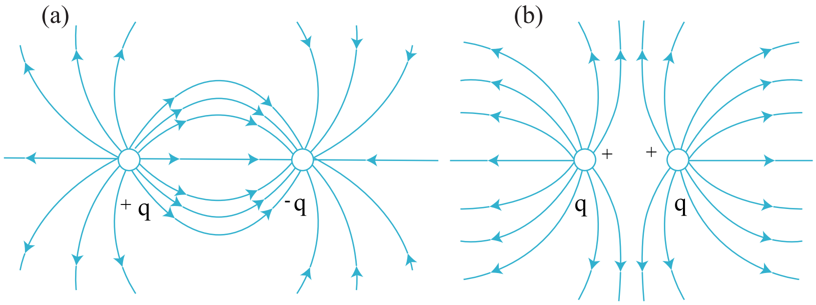


Figure 6. Lines of force of (a) opposite charges (b) similar charges

Electric potential difference

In this section, you will explore the relationship between voltage and electric field. Suppose a positive point charge q is released freely at point A inside a uniform electric field of magnitude E, as shown in Figure 8. Since the charge is positive, the charge carrying particle will accelerate in the direction of the electric field. The magnitude of the force exerted on the charge is given by

$$F = qE$$

The work done by this force to move it to point B, when the distance between the two plates, is

$$W = qEd$$

Plate A is at higher electric potential and B is at lower potential. Therefore, there is a voltage drop as we move from A to B, and hence this voltage drop should be negative, $-\Delta V = -V_{BA}$ and the work done on q can also be written as,

$$W = -q\Delta V$$

Using $-\Delta V = -V_{BA} = V_{AB}$, then equation (5.5) becomes

$$W = qV_{AB}$$

The potential difference V_{AB} between the two plates is obtained by combining equations W = qEd and $W = qV_{AB}$, to be

$$V_{AB} = Ed$$

The SI unit of potential difference V_{AB} is volt (V), where 1 V = 1 J/C.

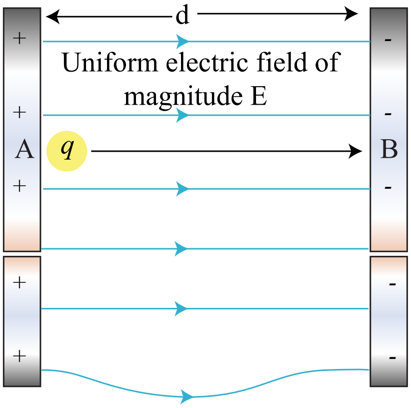


Figure 7. Charge in uniform electric field

Let us consider a point charge Q placed in vacuum. If we place another point charge q at a point P, at a distance r formed Q, as shown in Figure 6a, then the charge Q will exert a force on q as per Coulomb's law. Whether you remove q from point P or not, this property exists as long as charge Q is there. To find the electric field strength at point P, we measure the force exerted on q and the electric field strength $\vec{E}$ is determined by dividing the force by the point charge q, as

$$\vec{E} = \frac{\vec{F}}{|q|}$$

The SI unit of electric field strength is Newton per Coulomb (N/C). Since force is a vector quantity, so does the electric field.

According to Coulomb's law, the magnitude of the

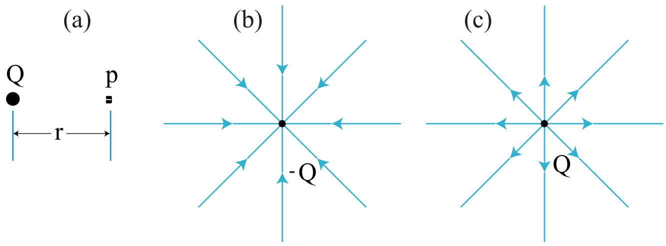


Figure 8. (a) Point near charge Q. (b) Field of negative charge. (c) Field due to positive charge

electric force between the two charges is $F = k|Qq|/r^2$, then the magnitude of the electric field strength of charge Q at point p is, then

$$E = \frac{k|Q|}{r^2}$$

The direction of the electric field strength is conventionally determined to be towards charge Q if it is negative charge (see Figure 6b) and away from Q if it is positive charge (Figure 6b).

Examples

When a charge of − 5 C is placed in a uniform electric field, it accelerates westward. If the magnitude of the force is 200 N, what is the magnitude and direction of the electric field strength?

Solution:

$F = 200\text{ N},\ q = -5\text{ C}$

The magnitude of the electric field is

$$E = \frac{F}{|q|} = \frac{200N}{5C} = 40N/C$$

Since the negative charge is accelerated westward, the force is also directed westward which is opposite to the direction of the force for a negative charge. So, the direction of the field is eastward.

Examples

When a charge Q is placed in an electric field of strength 1000 N/C, a force 400 N acts on it in the direction of the field. What is the magnitude and type of the charge?

Solution: E = 1000 N/C, F = 400 N

The magnitude of the desired charge is

$$Q = \frac{F}{E} = \frac{400N}{1000N/C} = 0.4C$$

Since the force is in the direction of the field, it is a positive charge.

Examples

What is the electric field strength at a point a distance 2m to the right of a positive, point charge of magnitude $0.5\mu C$?

Solution: $r = 2$ m, $Q = 0.5\,\mu C = 5\times10^{-7}\,C$

The magnitude of the electric field is

$$E = \frac{kQ}{r^2} = \frac{\left(9\times10^9\,Nm^2/C^2\right)\left(5\times10^{-7}\,C\right)}{(2m)^2}$$

$E = 1125$ N/C

Electric potential gradient

In Figure 8, plate A is at higher potential and B is a lower potential. As a positive charge accelerates towards plate B, its electric potential energy decreases with distance. In this case, the electric field can be defined in terms of the variation of electric potential at different points in the field. The potential gradient in an electric field is a vector, which is defined as the rate of change of electric potential with respect to displacement in the direction of the field. The magnitude of potential gradient is given by

$$E = -\frac{\Delta V}{\Delta r}$$

where E is electric field strength (V/m), ΔV is change in potential (V), Δr is displacement in the direction of the field (m).

Examples

A positive point charge of magnitude 1.5 μC is placed freely in a uniform electric field of strength 100 N/C. If the charge is traveled from point A to point B, which are 2 cm,

(a) What is the potential difference between points A and B? Which point is at higher potential?

(b) How much work is done on the charge by the field?

(c) What is the potential gradient?

Solution: $q = 1.5\,\mu C$, $E = 100$ N/C, $d = 2$ cm $= 0.02$ m

(a) The potential difference between points A and B, V_{AB}, is

$V_{AB} = Ed = 100\ N/C \times 0.02\ m = 2\ V$

(b) The work done on the charge is

$W = qV_{AB} = 1.5\,\mu C \times 2\,V = 3\,\mu J$

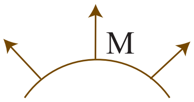
(c) Since the electric field is uniform we can take any interval. Thus, the potential gradient is

$$E = -\frac{\Delta V}{\Delta r} = -100\ V/m$$

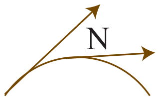
Exercises

1. What is electric field?
2. Draw the pattern of the electric field:
   - (a) around a positively charged large plate.
   - (b) around a negatively charged large plate.
   - (c) between two oppositely charged plates whose separation distance is very small compared to their dimensions.
3. The two curves in the figure represent electric lines of force in an electric field.

(a) Rays perpendicular to the curve



(b) Rays tangent to the curve



   - (a) Which arrows represent the electric field strength? in (a) or on (b)?
   - (b) if a positive test charge is placed on point N, what would be the direction of the force on it?
   - (c) If a point negative charge is placed on point N, what would be the direction of the force on it?
4. How much force does a +3 C charge experience if it is placed in a 30 N/C electric field?
5. A uniform electric field of strength 500 N/C moves a positive charge Q between two points a distance of 1 cm apart.
   - (a) What is the potential difference between the two points?
   - (b) If the work done is 10 μJ, what is the magnitude of Q?
6. Does the electric potential around a positive charge decrease or increase with increasing distance?

Upon completion of this topic you will be able to:

- identify/Describe the types of capacitors and their uses.
- discuss the relationship between potential difference and capacitance.
- solve problems on networks of capacitors.

When a source of potential difference and a load are connected by a conductor, an electric field sets up in the circuit and can cause charged particles to move. If there is a gap in the circuit, conduction electrons are generally unable to escape their conductor and move across the gap. This is why a complete path is needed for a simple electric circuit to function. However, charge can be made to flow in an incomplete circuit by connecting two large metal plates in a circuit with an air gap or some insulating substances between them. This is how the capacitor, which is the concern of this section, works.

Capacitor and Capacitance

A capacitor is a device used to store electrical charge or energy. They are made of a pair of two metal sheets that are situated in close proximity to each other and a small gap between them compared to their dimensions. The gap between the plates is either vacuum or filled with an insulating material called a dielectric.

When the two conducting plates are connected to a battery, electrons are removed from the plate connected to the positive terminal of the source and are added to the plate that is connected to the negative terminal of the source.

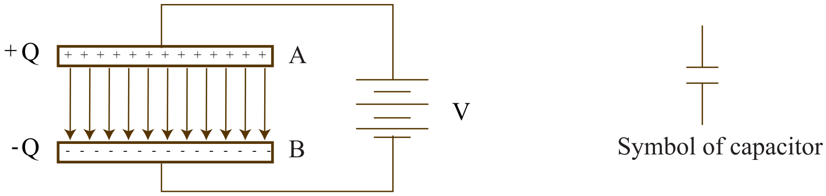


Figure 9. Charging parallel plate capacitor

The building of opposite charge on the plates gradually increases and continues until the potential difference between them (V_{AB}) is equal to the applied voltage (V). During the charging process, the charge stored in the capacitor is directly proportional to the potential difference developing between the plates. Therefore, we can define a proportionality constant as

$$C = \frac{Q}{V}$$

where C is called the capacitance of the capacitor. The SI unit of capacitance is farad (F), where, 1 F = 1 C/V. Capacitance is defined as the ability of a capacitor to store electrical charge and energy.

Examples

A capacitor of capacitance 200 pF is charged by a 1.5 V battery. How much charge is stored between the terminals of the capacitor? How much charge is stored on each plate?

Solution:

$C = 200\ \text{pF} = 2\times10^{-10}\ \text{F}$, $V = 1.5\ \text{V}$

The charge stored in the capacitor is

$$Q = CV = 200 \text{ pF} \times 1.5 \text{ V} = 300 \text{ pC}$$

The charge stored in the negative plate is −300 pC and that in the positive plate is +300 pC.

A number of capacitors can be connected in an electric circuit in three ways; namely, series, parallel; and series-parallel connections.

A. Series Connection of capacitors

Consider two capacitors with capacitance C1, and C2, are connected in series across a source of voltage V, as shown in Figure 10.

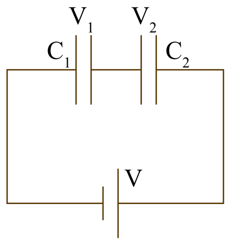


Figure 10. Capacitors connected in Series

To determine the equivalent capacitance of the circuit, the following two rules are helpful.

- The charge stored in each capacitor is the same as the total charge of the circuit

  $$Q = Q_1 = Q_2$$

- The potential difference across each capacitor is summed up to give the source voltage V.

  $$V_T = V_1 + V_2$$

Substituting V = Q/C, into this equation, we obtain

$$\frac{Q}{C_{eq}} = \frac{Q_1}{C_1} + \frac{Q_2}{C_2}$$

Since the same charge stores in all capacitors, all Q's will cancel out and we have

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2}$$

The reciprocal of the equivalent capacitance $(1/C_{eq})$ is the algebraic sum of the reciprocals $(1/C_1 \text{ and } 1/C_2)$ of the individual capacitances.

B. Capacitors in parallel

Two capacitors with capacitance C_1, and C_2 are connected in parallel to a source of voltage V, as shown in Figure 11.

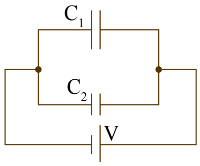


Figure 11. Capacitors connected in parallel

When capacitors are connected in parallel the following two rules are applied to the circuit

The total charge Q stored in the circuit is the algebraic sum of the charge stored across each capacitor.

$$Q = Q_1 + Q_2$$

The voltage maintained across each capacitor is the same as the total Voltage of the circuit.

$$V = V_1 = V_2$$

Using Q = CV into the second equation, and simplifying the result, we obtain the equivalent capacitance to be

$$C_{eq} = C_1 + C_2$$

The equivalent capacitance (C_{eq}) of the combination is the algebraic sum of the capacitance of each capacitor.

C. Series-parallel connection

Three capacitors are connected with each other and the source, as shown in Figure 12.

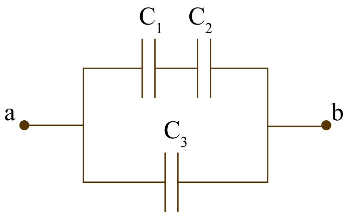


Figure 12. Series-parallel connection

Capacitors with capacitance C_1 and C_2 are connected in series. Net capacitance of the upper two capacitors is

$$\frac{1}{C_{eq1}} = \frac{1}{C_1} + \frac{1}{C_2}, \text{ or } C_{eq1} = \frac{C_1C_2}{C_1 + C_2}$$

Capacitor with the equivalent capacitance C_{eq1} is connected in parallel with C_3. Adding these two gives

$$C_{eq} = C_{eq1} + C_3 = \frac{C_1C_2}{C_1 + C_2} + C_3$$

$$C_{eq} = \frac{C_1C_2 + C_1C_3 + C_2C_3}{C_1 + C_2}$$

Examples

A 6 μF and 4 μF capacitors are connected in series. (a) What is the equivalent capacitance? (b) What would be the equivalent capacitance if the capacitors are connected in parallel?

Solution: $C_1 = 6$ μF, $C_2 = 4$ μF

(a) The equivalent capacitance when the two capacitors are connected in series is

$$C_{eq} = \frac{C_1C_2}{C_1 + C_2} = \frac{6\mu F \times 4\mu F}{6\mu F + 4\mu F}$$

$$C_{eq} = 2.4\mu F$$

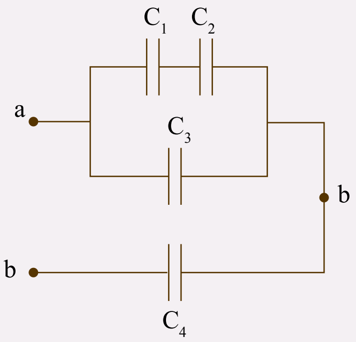
(b) The equivalent capacitance when the two capacitors are connected in parallel is

$$C_{eq} = C_1 + C_2 = 6\mu F + 4\mu F$$

$$C_{eq} = 10\mu F$$

Examples

In the circuit diagram shown in the figure, if C_1 = 6 μF, C_2 = 3 μF, C_3 = 5 μF, and C_4 = 4μF, find the equivalent capacitance?



Solution: C_1 = 6 μF, C_2 = 3 μF, C_3 = 5 μF, C_4 = 6μF

The equivalent capacitance Ceq1 of C_1 and C_2 is

$$C_{eq1} = \frac{C_1C_2}{C_1 + C_2} = \frac{6\mu F \times 3\mu F}{6\mu F + 3\mu F} = 2\mu F$$

Now C_{eq1} is connected with C_3 in parallel and the equivalent capacitance C_{eq2} becomes

$$C_{eq2} = C_{eq1} + C_3 = 2\mu F + 5\mu F = 7\mu F$$

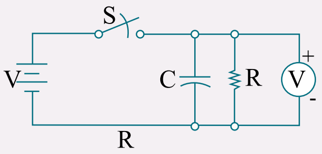
Then, C_{eq2} is connected with C4 in series and the equivalent capacitance C_{eq} becomes

$$C_{eq} = \frac{C_{eq2}C_4}{C_{eq2} + C_4} = \frac{6\mu F \times 4\mu F}{6\mu F + 4\mu F}$$

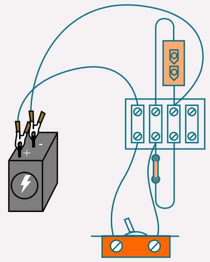
$$= 2.4\mu F$$

$$C_{eq} = 2.4\mu F$$

Discharging circuit in symbols



Discharging circuit



Activity 2

Experiment on charging and discharging a capacitor

The aim of this experiment, is to learn about capacitor charging action, capacitor discharging action, time constant calculation, and series and parallel capacitance.

In order to produce time constants slow enough to track with a voltmeter and stopwatch, large-value capacitors should be used. Materials required for this experiment are 6-volt battery, two large electrolytic capacitors (minimum of 1 mF), two 1 kΩ resistors, and one toggle switch, SPST ("Single-Pole, Single-Throw").

Precaution

- You are supposed to use large capacitors. Most large capacitors are of the "electrolytic" type, and they are polarity sensitive. Failure to heed the right polarity will surely result in capacitor failure, even with small source voltages. The failure results for the capacitor typically to explode, discharging caustic chemicals and emitting foul odors.

Experiment Instructions

- Build the "charging" circuit and measure voltage across the capacitor when the switch is closed.
- Notice how it increases slowly over time, rather than suddenly as would be the case with a resistor. You can "reset" the capacitor back to a voltage of zero by shorting across its terminals with a piece of wire.
- The "time constant" (τ) of a resistor-capacitor circuit is calculated by taking the circuit resistance and multiplying it by the circuit capacitance. $\tau = RC$ is the amount of time it takes for the capacitor voltage to increase approximately 63.2% from its present value to its final value: the voltage of the battery.
- The discharging circuit provides the same kind of changing capacitor voltage, except this time the voltage jumps to full battery voltage when the switch closes and slowly falls when the switch is opened. See circuits in the figure.

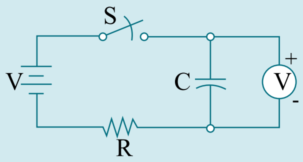
If your RC value is too small to be noticed, you can think of a way of slowing down the time constant in two different ways:

(a) Changing the total circuit resistance, and/or

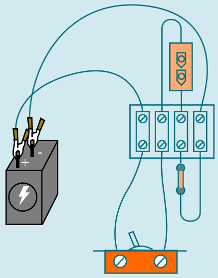
(b) Changing the total circuit capacitance.

Use a pair of identical resistors and a pair of identical capacitors, then experiment with various series and parallel combinations to obtain the slowest charging action.

Charging circuit by symbols



Charging circuit



Questions

1. Have you achieved your objectives?
2. What are your time constants, in discharging and charging a capacitor?
3. Mension problems you faced and discuss solutions.

Some applications of capacitors

A capacitor is a primary storage device widely used to store electric charge or electric energy in electric field and release them whenever required. Almost every electronic device needs Capacitors. Different electric circuits require different kinds of capacitors based on their application types. Some of the various applications of a capacitor used in different electrical industries are discussed below.

A. Energy storage

The primary application of a capacitor is storing electric energy when it is connected to an electric circuit. This capacitor can consume the stored energy after it is disconnected from the circuit and it can work as a temporary battery. Capacitors are usually used in electric devices to control the power supply while batteries are being changed. Therefore, it helps to prevent the loss of data in volatile memory.

B. Smoothing circuits

Most electrical devices make use of d.c. currents, but the current from the mains is a.c. Therefore, a device to convert a.c. to d.c is required. A device called a rectifier is used to convert a.c to d.c. A rectifier will supply a current that varies with time. In a rectifier, there is a system that converts the a.c to a pulsating d.c. Finally, the capacitor converts the pulsating d.c to a smooth d.c. During a cycle, the capacitor charges up when current is supplied and discharges through the load resistor when no current is supplied. The current with the capacitor in place is shown in Figure 13.

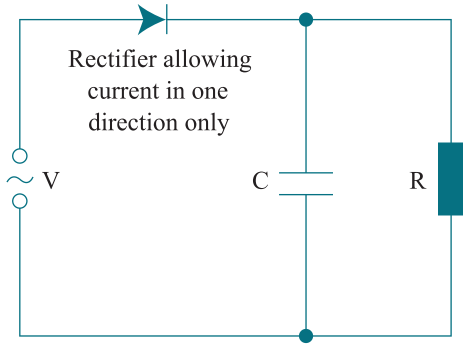


Figure 13. Smoothing circuit

C. Filter circuits

Filter circuit is designed circuits in which high-frequency signals travel in one direction in a circuit and low frequencies travel in another. Such a circuit has several applications. For example, in radios or other similar devices, unwanted noise can be diverted from entering a loudspeaker.

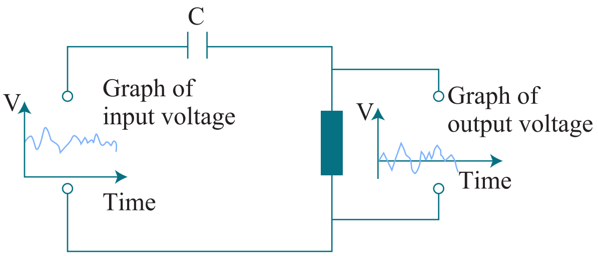
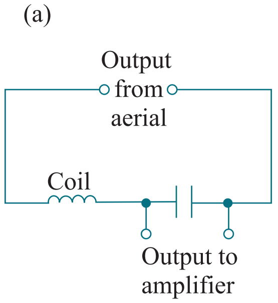


Figure 14. A direct current blocking circuit

Another important application of filter circuit is that when mixed a.c and d.c currents pass through a circuit, the circuit blocks the d.c current and allows only a.c currents to pass through.

D. Tuning circuits

Tuning circuits are combinations of a variable capacitor and a coil, connected in series. A signal of a particular frequency will give a large output.



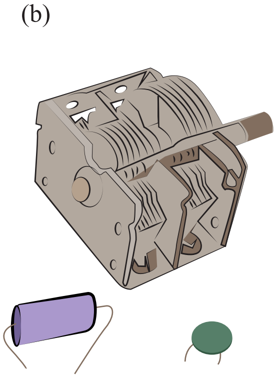
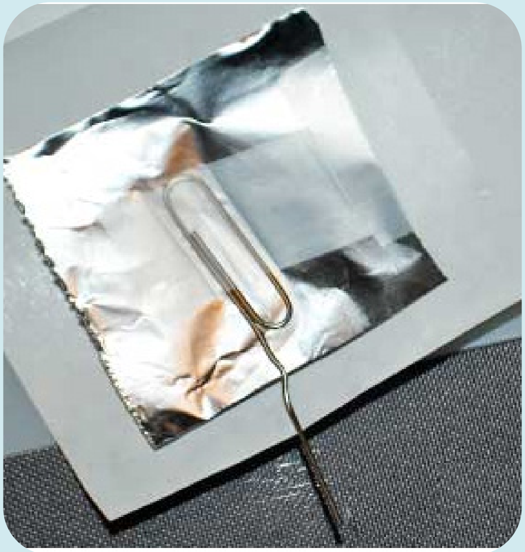


Figure 15. (a) A tuning circuit (b) A variable tuning capacitor

Activity 3

Design to build capacitor

In this activity, you will design how to construct a capacitor using aluminum foil, wax paper, and masking tape. Use your digital multimeter to measure the capacitance of each one. Your multimeter must be in capacitance mode to make these measurements and the reading is in nanofarads.



- Cut two squares from the aluminum foil strip. Trim the wax paper so it is about one-fourth to half inch wider than the aluminum foil on the top and bottom.
- Bend one end of each of the two paper clips so they are straight. Attach these paperclips on one face of each foil as shown in the figure.

- Fold the wax paper so the aluminum foil square is covered on each side with the dielectric (wax paper).
- Place the second aluminum square foil directly over the same location of the other square foil. Use a little piece of tape on top to secure it in place. Tape the curved end of the remaining paperclip to the middle of the aluminum foil square and position the straight piece so it extends beyond the side of the wax paper in the opposite direction of the first paperclip.
- Fold the remaining length of wax paper over the top of the aluminum foil square so it is not exposed.

- Use 3 V d.c power supply to charge your capacitor. You can connect your capacitor to the battery using alligator clips.
- Remove the alligator clips from the ends of the battery holder and connect them to a multimeter. Before the connection, set the multimeter to read DC voltage in microvolts. This is to test the homemade capacitor to see if it can store electricity.
- Measure capacitance of a standard capacitor. A 1000 microfarad capacitor had about the same voltage reading as our home-made capacitor.

Questions

1. Which properties of the capacitor determine its capacitance; the surface area of each plate, type of conductor the plates are made, the type of material inserted between the plates?
2. How did your experiment perform? If you were having trouble, identify the cause and give solutions.
3. If you squeeze the capacitors, does the capacitance change? Explain about this.

Exercises

1. You have learnt about parallel plate capacitor. Is there any possibility to construct a capacitor with a different shape?
2. What are the main components of capacitor?
3. What is capacitance?
4. A 2.5 μF capacitor is charged from a 12.0 V battery. How much charge will it hold?
5. Given three capacitors of capacitance 4 μF, 5 μF and 3 μF. Connect these three capacitors in three different ways and find the equivalent capacitance for each.
6. Explain the charging and discharging of a capacitor.
7. A photographic flash unit has a 120 μF capacitor which is charged up by a 25 V battery. How much charge is stored in it?

SUMMARY

- Matter possesses a property called electric charge and there are only two kinds of electric charges: positive charge and negative charge.
- The charge carried by a proton or an electron is the ultimate natural unit of charge whose magnitude (e) is

  $$e = 1.602 \times 10^{-19}\,C$$

- Materials which permit the flow of charge through them are called conductors of electric current. On the other hand, materials like the nylon cord that do not allow the flow of electric current through them are called insulators.
- Electrically neutral objects can be electrified by rubbing (friction), by sharing (conduction) and by induction. By rubbing, objects are charged oppositely; by touching or by sharing, objects are charged similarly; and by induction bodies are charged oppositely.
- The interaction between any two charges is governed by the basic laws of electrostatics, which are stated as, "like charges repel each other and unlike charges attract each other".
- The force of interaction of two electrostatic point charges in vacuum is directly proportional to the product of the two charges and inversely proportional to the square of their separation.
- The magnitude of the force between two point charges q_1 and q_2 which are at a distance r apart, is given by Coulomb law as

  $$F = \left(9 \times 10^{9}\,Nm^2/C^2\right)\frac{|q_1||q_2|}{r^2}$$

- If a force of electrical origin is exerted on the test charge, then an electric field exists at the point.
- The magnitude of the electric field strength due to charge Q at a point a distance r from the charge is given by

$$E = \frac{k|Q|}{r^2}$$

- The direction of the electric field strength is conventionally determined to be towards charge Q if it is negative charge and away from Q if it is positive charge.
- Electric field can be visualized as consisting of imaginary lines called electric lines of force. Each line corresponds to the path that a positive test charge would take if it is placed in the field on that line.
- The potential difference between two points in a uniform electric field at a distance d is

$$V_{AB} = Ed$$

- The electric field strength between any two points at a distance Δr and having p.d ΔV is

$$E = \frac{\Delta V}{\Delta r}$$

- The expression $\Delta V / \Delta r$ is called potential gradient.
- A capacitor is a device used to store electrical charge and energy. During charging a capacitor, the charge stored in the capacitor is directly proportional to the potential difference developing between the plates. Therefore, we can define a proportionality constant as

$$C = \frac{Q}{V}$$

- Capacitance is defined as the ability of a capacitor to store electrical charge and energy.
- When several capacitors are connected in series, the equival9ent capacitance is

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + ...$$

- When several capacitors are connected in parallel, the equivalent capacitance is

$$C_{eq} = C_1 + C_2 + \ldots$$

Exercises

1. Explain a method how to produce two charged objects that attract or repel each other.
2. How does potential difference related to electric field strength?
3. What is the potential difference between any two points which are equidistant from a charge?
4. What is a capacitor? What is capacitance?
5. Describe some uses of capacitors in everyday life.
6. What is the magnitude of the electrostatic force acting between two charges of magnitudes 5 μC and 6 μC, which are 3 cm apart?
7. Determine the force that a 6 C charge experiences when it is placed in an electric field of strength 25 N/C.
8. What is the magnitude of the electric field strength at a point a distance of 25 cm from a charge of +0.8 nC?
9. The electric field strength in a region is uniform and its magnitude is 2.5×10^6 V/m. If the potential difference between two points, A and B, located in the field, is 100 V, what is the separation distance between the two points?
10. Suppose an electron gun has parallel plates that are separated by 5 cm. The field can do a total work of 0.2 J on a piece of plastic carrying a charge of 8 μC to move the charge from one plate to the other.
    (a) What is the potential difference between the plates?
    (b) What is the electric field strength between the plates?
    (c) What force would this field exert on the piece of plastic?
11. The electric field strength between two parallel conducting plates separated by 2 cm is 5×10^4 V/m.
    (a) What is the potential difference between the plates?
    (b) What is the potential difference between one plate and a point at a distance of 1 cm?
12. The electric field strength between two parallel plates is 4 kV/m. How far apart are two conducting plates if their potential difference is 20 kV?
13. A 10 μF capacitor is charged by a 3 V battery. How much charge is stored in the capacitor?

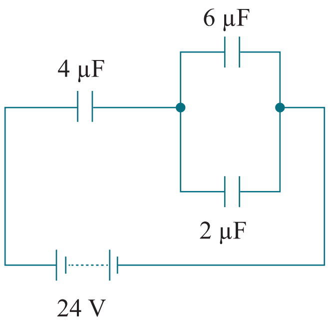
14. Given two capacitors of capacitance 5 μF and 15 μF, which arrangement gives the highest capacitance?

15. Three capacitors are arranged as shown in the figure below. Calculate

    (a) the total capacitance of the system,

    (b) the total charge on the circuit, and

    (c) the potential difference between the terminals of the 4 μF capacitor.

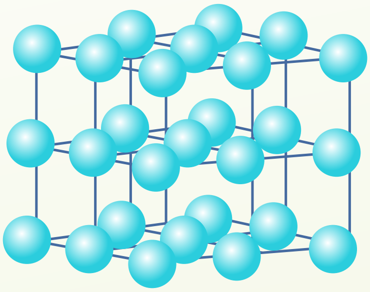


P10CH06

CHAPTER 6

PROPERTIES OF MATTER

Chapter Contents



Chapter Outcome

You will be able to:

- recognize the structure of matter and determine the effect of applied force due to Hooke's Law.

Introduction

Most of the observable characteristics of system of matter with which we are familiar represent bulk properties of matter, i.e., the properties associated with a collection of a large number of atoms, ions or molecules. For example, an individual molecule of a liquid does not boil but the bulk boils. Collection of water molecules has wetting properties; individual molecules do not wet. However, properties of single particle have significant effect on the properties of the bulk matter. Therefore, before going into some properties of the bulk matter you will study the structure of matter to the molecular or single particle level.

You may remember that under normal conditions substances exist mainly in one of the three major states of matter: solid state, liquid state, and gaseous state of matter. The existence of matter in any of these states depends on the balance between the attractive intermolecular forces and dispersive forces due to thermal energy in the system. In this unit, you will learn about observable properties of matter; dependence of observable properties on the microscopic (atomic/molecular) properties; about attractive and repulsive intermolecular force and forces due to thermal energies, on the basis of the kinetic theory of matter. And you will also look at some of the physical properties of the liquids such as surface tension and viscosity and their dependence on intermolecular forces. You will also learn about elastic and plastic behaviors of matter on the basis of Hooke's law.

Upon completion of this topic, you will be able:

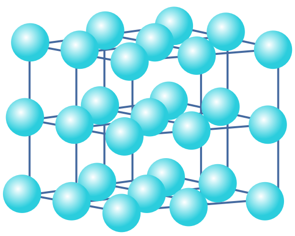
- distinguish between atoms and molecules

Anything in the universe that has mass and volume is made up of matter. Matter exists in three different states and it changes from one state to another due to the internal and external factors. You will learn properties of matter in the three states.

States of matter

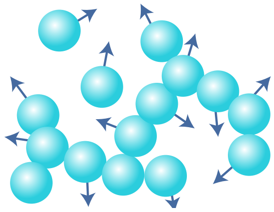
Matter exists in different forms due to some internal and external factors. The states of matter depend on the large scale properties; namely, temperature and pressure. At a given temperature and pressure, a substance can exist mainly in one of three major states of matter: solid state, liquid state, and gaseous state of matter.

Solid: - Atoms or molecules of solids are held close to each other by attraction forces which have electrostatic origin. They will bend and/or vibrate, but are locked in position. The molecules have an ordered arrangement. All these gives them definite shape and definite volume



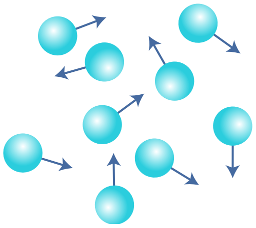
Solid

Liquid: - Molecules in liquids can flow or glide over one another. Their kinetic energy is strong enough to slip out of the ordered arrangement of a solid. In this case, liquids do not have definite shape. However, they stay toward the bottom of the container and hence possess fixed volume. Motion is a bit more random than that of a solid.



Liquid (Shorts arrows to show small speed)

Gas: - Molecules in gas are in continual straight-line motion. The kinetic energy of the molecule is greater than the attractive force between them. The gap between molecules is very wide. The movement of the particles is assumed to be random and free. In this case, liquids have neither definite shape nor definite volume.



Gas (longer arrows to show faster speeds)

Figure 1. Comparing structure of water molecules in the three different phases

Phases of matter vs states of matter

A phase of matter is when all the physical properties within a material are uniform. At a given phase of matter a material will have the same density and refractive index. For example, a cube of ice (solid water) is at one phase, liquid water is in another phase and water vapor is the third phase.

States of matter are classifications of the distinct phases of matter based on their large-scale properties. For example, a solid phase is the state in which the substance maintains a fixed volume and a fixed shape, whereas the liquid phase is one where the substance can change to take the shape of its container.

Changes in state of matter

A phase change occurs when a substance changes state. For example, when ice (solid) converts to water (liquid), which then turns to vapor as the temperature increases. The decrease in temperature changes the phase from gas to liquid and then to solid. A change of state undertakes when the average kinetic energy of the molecules (or temperature) in the substance changes.

KEY TERMS

- **Phase (of matter)** point at which all the physical properties within a material are uniform

A phase change is not a chemical change but it is a physical change. Physical properties of a substance depend upon its physical state. For example, water vapor, liquid water and ice all have the same chemical properties, but have considerably different physical properties.

The phase diagram, shown in Figure 6.2, indicates the triple point for the substance, which is the point where all the three states coexist together. This occurs at a temperature of 0°C for water. At the critical point the liquid and the gas phases become indistinguishable.

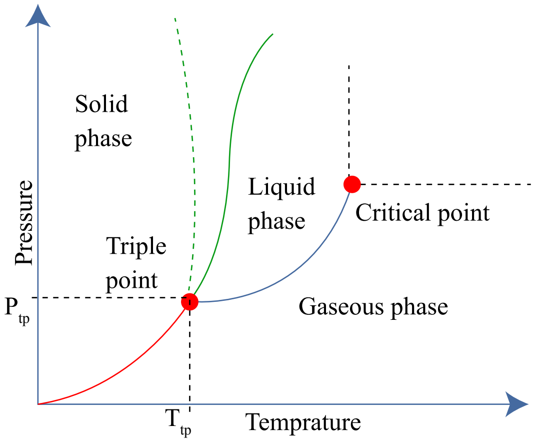


Figure 2. A phase diagram showing different states of matter

Matter is made up of microscopic units called atoms. Chemical elements are composed of atoms of a certain type. An atom has a central nucleus and one or more electrons moving around the nucleus. An atom consists of a positively charged atomic nucleus (protons and neutrons) and a negatively charged electron shell (electrons), as shown in Figure 6.3. Since a proton and an electron carry equal and opposite charges, an atom that has the same number of electrons in shells as it has protons in its nucleus is electrically neutral. The nucleus of every atom except that of the smallest isotope of hydrogen also contains one or more neutrons, which are electrically neutral. The number of protons and neutrons in the nucleus of an atom uniquely determines the element it represents such as iron, zinc, copper, oxygen, and so on. Sizes of an atom and that of its particles are shown in the figure.

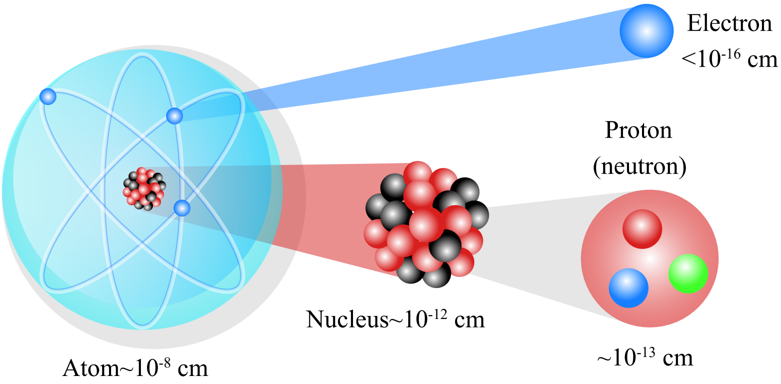


Figure 3. The structure of an atom

Chemical bonds

Atoms may or may not exist independently, but most of them undertake chemical reactions to form ions and molecules which further combine in large numbers to form matter that we see, feel and touch. A compound is a distinct group of atoms held together by chemical bonds. Just as the structure of the atom is held together by the electrostatic attraction forces, the stability within chemical bonds is also due to electrostatic attractions. There are two major types of chemical bonds: covalent bonds and ionic bonds.

Key Terms

- **Particle:** all atomic units such as molecules, atoms, protons, neutrons, electrons, etc. are simply referred to as particles.

- In covalent bonds, two or more atoms share pairs of electrons like water molecule,
- In ionic bonds; electrons are fully transferred between two atoms so that ions are formed. For example, electron transfers from sodium to chlorine atom to form sodium chloride (table salt). Thus, sodium chloride is an ionic compound and is not a molecule.

A molecule is the simplest unit of a covalent compound that contains the physical and the chemical properties of the compound. Some examples of molecules are H_2O (water), N_2 (nitrogen), and O_3 (ozone).

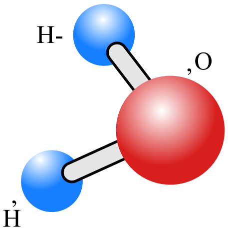
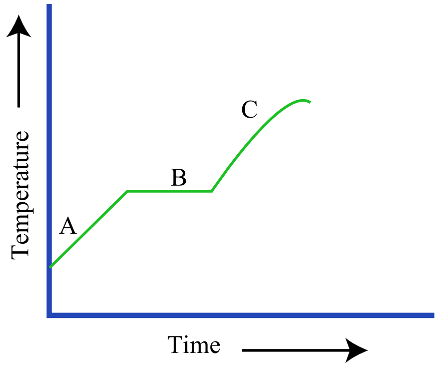


Figure 4. Water molecule

Exercises

1. Among the three states of matter, in which state of matter are particles packed tightly together in fixed positions?
2. In which state of matter are particles arranged in either a crystalline or an amorphous form?
3. In which state of matter do the particles spread apart and fill all the space available to them?
4. Which state of matter undergoes changes in volume most easily?
5. The figure shows how the temperature of a substance changed as it was heated. Which segment of the graph indicates that the substance was undergoing a change of state?



6. If you find water cooled and changed to ice, then can you conclude that the temperature of the water is 0°C without undertaking measurement?
7. What is intramolecular force?
8. Is a change in state of matter a result of chemical or physical change?

Upon completion of this topic, you will:

- examine the kinetic theory of matter
- distinguish between cohesion and adhesion

You have learnt that substances exist in different physical states. For example, water exists as water, ice and steam. When water undergoes a change in state, it is only a physical change. Its chemical properties do not change; it is still the same H_2O molecule. However, the rate at which the chemical reactions occur can change with the physical state. To understand how and why a substance undergoes a change in its state of matter, you must know how the inter-molecular forces and the thermal interactions affect the substance. The kinetic theory of matter which is used to describe matter with a good approximation is also the concern of this topic. Here you will also learn about cohesion and adhesion, which are results of intermolecular force.

The Kinetic theory of matter

The kinetic theory of matter offers a description of the microscopic properties of atoms (or molecules) and their interactions, leading to observable macroscopic properties (such as pressure, volume, temperature). One important application of this theory is that it helps to explain why matter exists in the three different phases as discussed above and how matter can change from one state to the next.

This theory is based on the following assumptions:

- Matter is made up of very tiny particles that are constantly moving.
- All particles in a sample substance possess kinetic energy that varies depending on the temperature of the sample. This in turn determines whether the substance exists in the solid, liquid, or gaseous state. Particles in the solid phase have the least amount of kinetic energy, while gas particles have the greatest amount of kinetic energy.
- The temperature of a substance is a measure of the average kinetic energy of the particles.
- A change in phase undertakes when the average kinetic energy of the particles is changed.
- There are spaces between particles of any matter. The average amount of empty space between molecules gets progressively larger as a sample of matter changes from the solid to the liquid and then to gas phases.

There are attractive forces between atoms/molecules, which get stronger and stronger as the particles move closer together. These attractive forces are called van der Waals forces or van der Waals bonds, or attractive intermolecular forces.

Intermolecular forces and Thermal energy

Intermolecular forces are either the forces of attraction or forces of repulsion between interacting molecules. When two molecules come very close to each other, the repulsion between the electron clouds and that between their nuclei comes into play. The magnitude of the repulsion rises very rapidly as the distance separating the molecules decreases. This type of force is the repulsive intermolecular force. This repulsive force limits the compression level of liquids and solids.

Attractive intermolecular forces are known as van der Waals forces. Force example, molecules of liquid water is attracted to each other by electrostatic forces that are known as van der Waals forces or van der Waals bonds. The charge distribution in water molecule is not symmetrical and leads to a microscopic separation of the positive and negative charge centers. That is, the hydrogen will be slightly positive with respect to the oxygen, which has high elecronegativity even though the molecule as a whole is still electrically neutral. This charge separation is the cause of van der Waals force.

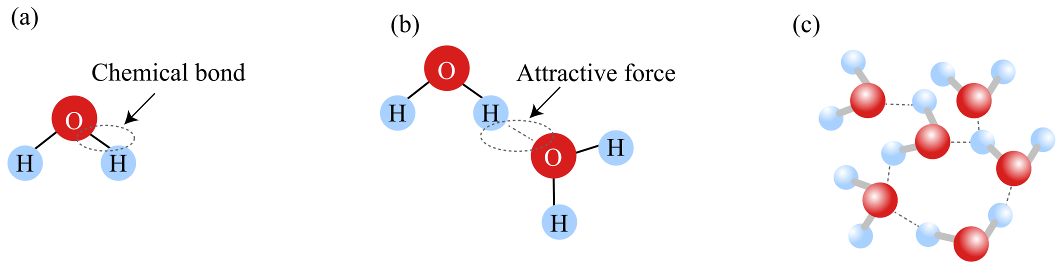


Figure 5. (a) Chemical bonds- determine molecular shapes, bond energies, and chemical properties (b) van der Waals bonds- determine only physical properties of liquids and solids (c) Structure of water

Non-polar molecules also experience some van der Waals bonding. Such molecules do not have permanent electric poles but they can have instantaneous electric poles which change or oscillate with time. These fluctuating molecular polarities lead to a net attraction force between molecules which allow non-polar substances to form liquids. The electric field from one instantaneous electric pole tends to polarize a neighboring molecule so that it will be attracted.

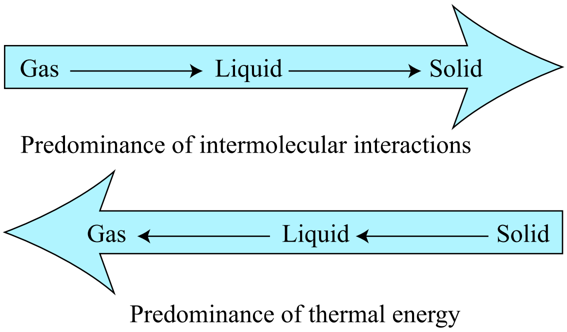
Thermal energy is the energy of a body arising from motion of its atoms or molecules. It is directly proportional to the temperature of the substance. This movement of particles is called thermal motion. The force due to thermal energy of molecules acts opposite to the attractive intermolecular force, and it is a dispersive force.

van der Waals force vs forces due to thermal energy

The attractive intermolecular forces tend to keep the molecules together by canceling out the dispersive force due to the thermal energy of the molecules. The three states of matter are results of balance between intermolecular forces versus the thermal energy of the molecules.

If the intermolecular interactions are very weak, molecules will not cling together to make liquid or solid unless thermal energy is reduced by lowering the temperature. A gas can be liquefied by compressing it until its molecules come very close to each other and intermolecular forces start to operate to the maximum. However, the easiest way to liquefy a gas is to reduce thermal energy of molecules by lowering the temperature.

Predominance of the thermal energy vs predominance of the molecular interaction energy of a substance in the three states is depicted as follows:



Now let us revise states of matter in terms of thermal motion vs intermolecular forces.

- Under normal conditions of temperature and pressure, the intermolecular force between molecules in a gas is very weak to balance the force due to the thermal energy. This condition allows the gas to expand to fill its container of any volume.
- The attractive intermolecular force among liquid molecules stronger than that in gaseous state. Under normal conditions of temperature and pressure, molecules in liquids are very close with each other that there is very little empty space between them. However, the intermolecular force cannot overcome the force due to the thermal energy so that the liquid retains fixed shape like solids.
- The intermolecular forces between neighboring molecules in solids are strong enough to keep them locked in position. As a result, a solid substance maintains fixed volume and a fixed shape.

Cohesion and Adhesion

You have learnt that attractive intermolecular forces exist between particles of substances. The attractive forces between like molecules are referred to as cohesive forces. For example, the molecules of a water droplet are held together by cohesive forces.

The attractive intermolecular forces between unlike particles are said to be adhesive forces. When two objects with unlike particles are brought in contact, the system experiences both adhesive and cohesive forces. Consider a capillary tube (tube of small diamater) dipped vertically into water and mercury as shown in Figure 6.6. The adhesive forces between water molecules and the walls of a glass tube are stronger than the cohesive forces between the water molecules. This is the reason why we see an upward turning meniscus at the walls of the vessel. This property contributes to capillary action. On the other hand, the adhesive forces between mercury atoms and the walls of a glass tube are weaker than the cohesive forces between mercury molecules.

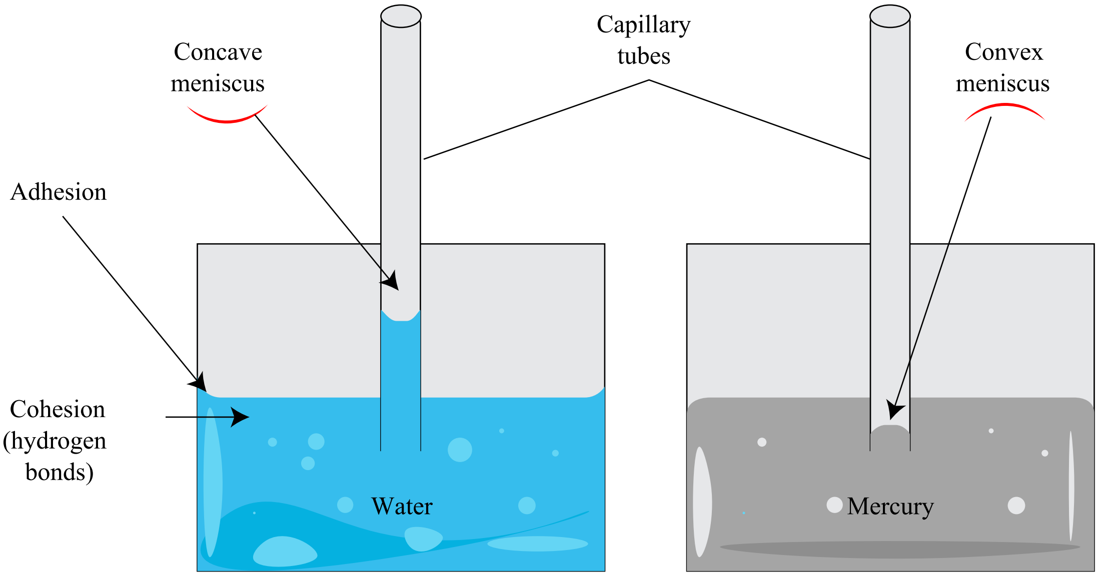


Figure 6.Capillary action

Activity 1

Demonstrating cohesive and adhesive forces

Two items are needed for the first part of the experiment to demonstrate the cohesive and adhesive forces of water: A pair of glass slides, and water.

How to do the demonstrations

- Put one surface of the glass slide onto the surface of the other.
- Try to slide one over the other? What do you observe?

Next

- Use a syringe to add a drop of water to the surface of one of the slide and add food coloring to the water to make the water more visible. Observe the shape of the drop.
- Place another slide on the first, with the water drop sandwiched between the two slides.
- Let you try to pull the slides apart, and to actually feel the strength of the intermolecular forces of water holding the slides together. What do you observe?
- Attempt to pull the slides apart, but only by pulling perpendicularly to the surfaces of the slides. What did you observe? Discuss.

Precaution

The demonstration will not work well if the slides get dirty or if too much water is used. Clean the slides before use if they are dirty.

Activity 2

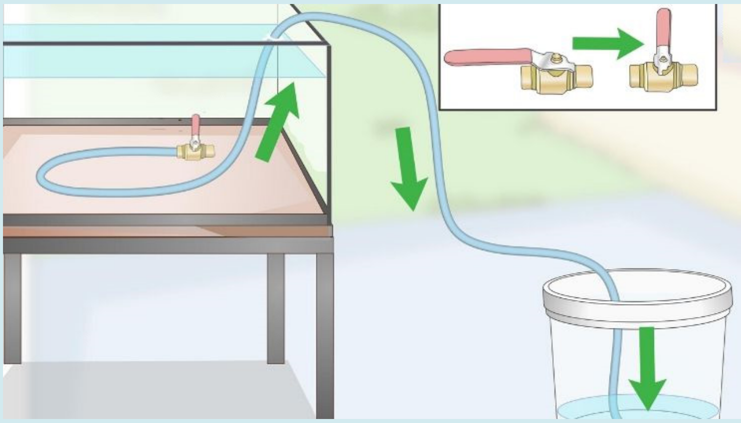
Experiment with Water Siphon to show water flowing upward due to gravity and cohesive force of the liquid

Do you ever see water going up a tube without the use of any external force? Of course, if there is a pull at the top end, water moves up. Otherwise no, right? But it is possible. Do this simple water siphon experiment to see water flowing up a tube, with nothing to pull it.

Using the siphoning technique, water flows from a container at a higher level all the way to the container at the lower level with the help of a transparent tube. This continues till water reaches same level in both containers. A step-by-step explanation will help you understand better.

Materials Required

- Container – 2 (preferably made of transparent glass)
- Flexible transparent tube – 1
- Water
- Food color (optional, to give that magical effect)



Steps To Follow

1. Fill water in both containers. The first container should be half-filled and the second container should be one-fourth filled with water.
2. Add food color to the container with more water.
3. Place the colored water in a slightly elevated position.
4. Now take the transparent tube, and dip one end of it in the colored water.
5. Suck water through the tube, so that the tube is entirely filled with water.
6. Close the end of the tube with your fingers. Be careful, no air should enter the tube.
7. Now place this end of the tube in the lower container with clear water. Make sure that one end of the tube is still immersed in colored water.
8. After dipping the end of the tube in the second container, slowly open your fingers.
9. What do you observe?

Exercises

1. What is intermolecular force?
2. Is there any atrractive force between atoms of noble gases? If yes, what type of force?
3. What is the cause of intermolecular repulsion force?
4. What is van der Waals force?
5. The charge distribution in water molecule is not symmetrical. Does this have contribution to the cohesion of water molecules?
6. Is hydrogen bonding a type of van der Waals bonding?
7. Do non-polar molecules experience van der Waals bonding? How?
8. What would be the strength of surface tension if the van der Waals force is weak as is seen in Non-polar liquids? What would be the impact on boiling points; low or high?
9. What is thermal energy?
10. What is the relationship between thermal energy and temperature?
11. Is the force due to thermal energy attractive or repulsive?
12. What is the easiest way to liquefy gas; to reduce or to increase thermal energy?
13. What do we call its structure if a solid adopts a highly ordered packing arrangement?
14. What are adhesive and cohesive forces?
15. Which force has an impact on capillarity action?

Upon completion of this topic, you will:

- analyze Hooke's law and apply Young's modulus in solving problems

This section outlines the basic mechanics of elastic responses, a physical phenomenon that materials often (but do not always) exhibit. You will learn that two equal and opposite forces cause deformation (change in shape and size) on objects. Types of responses that materials exhibit to deformations depend on whether the materials are elastic or plastic. An elastic material is one that deforms immediately upon loading, maintains a constant deformation as long as the load is held constant, and returns immediately to its original shape when the load is removed. This section deals with one of the physical quantities, which measures the amount of tensile deformation known as Young's modulus. Before this, you will learn other concepts such as stress and strain, which are related to Young's modulus. Elasticity is also elaborated using tensile stress vs tensile strain graphs. Equations that describe tensile/normal stress, tensile strain, and Young's/Elastic modulus are also used. Calculations are also used to determine the work done against elastic force of stretching spring.

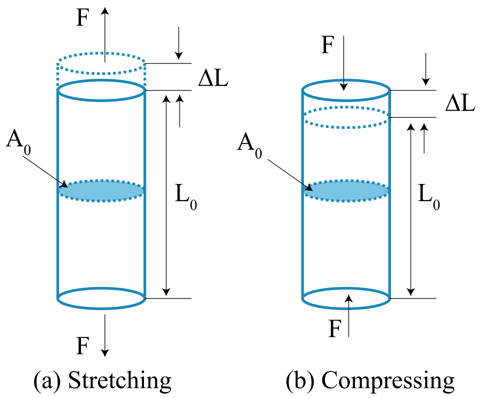


Figure 7. Tensile forces

Elasticity and plasticity

An object is said to be deformed by external forces if it is stretched, squeezed or twisted. After the removal of the external force, the object may or may not restore its original shape or size.

- If the object completely restores its original shape or size after the removal of the force, it is said to be perfectly elastic object.
- If an elastic object restores its original shape or size after the removal of the deforming force, such a deformation is called elastic deformation..

Elasticity is the property of matter by virtue of which the deformed body returns to its initial configuration after the removal of the deforming force. All objects behave as perfectly elastic bodies until the deforming force reaches to a certain limit. The maximum force that the object can withstand without being permanently deformed is called the elastic limit. The nature of the substance of which the material is made, is one of the factors that determine the elastic limit of a material.

Plastic deformation is deformation where irreversible changes occur on shape or size after it is being deformed even after the removed of the deformaly. Objects that are permanently deformed by a force are called plastic objects. An object is said to be plastic if it experiences a deforming force of magnitude beyond its elastic limit.

Stress and strain

The relative displacements of the various parts of an elastic body under the action of an external force produce an internal force tending to restore the body to its original configuration. Such internal force, generated in the body by the external force per unit area of the body is known as stress.

According to Newton's third law, if the system in the body is in equilibrium, the internal force is equal in magnitude but opposite in direction to the applied force. In this case, the externally applied force per unit area of the body in a state of equilibrium measures the stress.

The kind of deformation on a body depends on the way forces are applied. There are applied.

There are four types of deformations, three of which are shown in Figure 7.

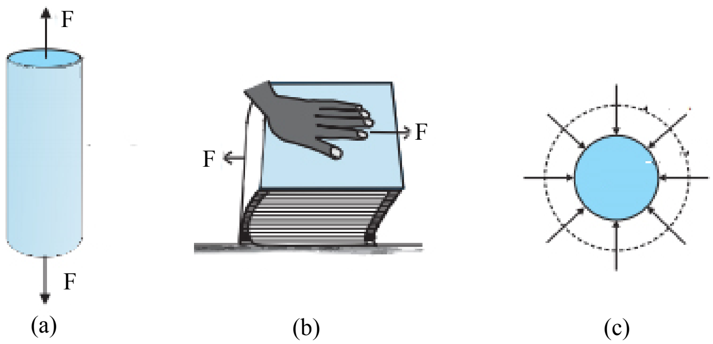


Figure 8. (a) Cylinder subject to tensile force, (b) Book under shearing force, (c) Solid sphere under uniform hydraulic force

In this section, we will focus on tensile deformation and in the next section, shear deformations may be considered.

Tensile deformation

Tensile deformation occurs when two forces of equal in magnitude and opposite in direction act perpendicularly on the cross-sections of opposite ends of a material such as a rod or a wire, as shown in Figure 6.8. A tensile force may stretch/elongate or compress a body. The quantity called stress, determines the amount of deformation. The type of stress produced by tensile/normal forces is referred to as the normal stress, or tensile stress. Tensile stress is defined as the ratio of tensile force (F) to the cross – sectional area A of the wire.

$$\text{Tensile stress} = \frac{F}{A} \qquad (6.1)$$

The SI unit of stress is newton per square meter (N/m^2).

The amount of deformation on a body can be measured by a quantity known as tensile strain of the body. Tensile strain is defined as the fractional change in length; i.e., the ratio of the extension L produced by the tensile stress to the original length (L_0) of the wire.

$$\text{Tensile strain} = \frac{\text{Extension on the wire}}{\text{Original length}} = \frac{\Delta L}{L_0}$$

$$\text{Tensile strain} = \frac{\Delta L}{L_0} \qquad (6.2)$$

Tensile strain is just a pure number without a unit as it is a ratio of two lengths.

Elastic (young's) modulus

The stress applied to a wire produces a strain in it. Young's modulus or elastic modulus (Y) is defined as a ratio of tensile stress to the resulting tensile strain. Mathematically,

$$\text{Young's Modulus} = \frac{\text{Tensile stress}}{\text{Tensile strain}}$$

$$Y = \frac{F/A}{\Delta L/L_0} = \frac{FL_0}{A\Delta L} \qquad (6.3)$$

The SI unit of Young's modulus is N/m^2.

Young's modulus characterizes elastic properties of materials under tensile forces independent of its size or shape. The elastic modulus is the measure of the stiffness of a material. In other words, it is a measure of how easily any material can be bent or stretched.

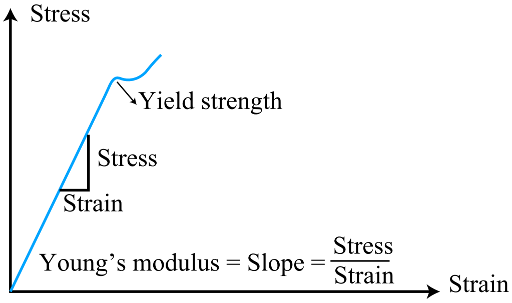


Figure 9. Stress-strain graph

The strain-stress curve, shown in Figure 6.9, is a graphical way to show the reaction of a material when a load is applied. You can see that the elastic modulus is the slope of stress and strain diagram up to the limit of proportionality. The graph of stress against strain is linear or a straight line only for stresses below the elastic limit labeled as yield strength.

The elastic limit of a material depends on its internal structure. For example, most metals such as Aluminium and copper have a low elastic limit while most non-metals such as rubber have a high elastic limit. Based on this property, materials can be categorized as ductile, brittle or malleable.

- A material is said to be ductile if it is drawn to a wire. Metals are dectile.
- There are materials that have no plastic stage at all before they break. Such materials are described as brittle.
- Materials that can fold or roll easily into sheets is called malleable. Metals are malleable.

Examples

A 5 m long steel wire has a cross-sectional area of 4 mm^2. It hangs from a tall ceiling, and a load of 0.6 kg mass is attached to its end. What is tensile strain on the wire?

Solution: $L_0 = 5$ m, $A = 4 \times 10^{-6}$m^2, m = 0.6 kg, $Y = 2 \times 10^{11}$ N/m^2

The tensile strain can be derived from Young modulus to be

$$\text{Tensile Strain} = \frac{\Delta L}{L_0} = \frac{F}{AY} = \frac{mg}{AY}$$

$$\text{Tensile Strain} = \frac{(0.6\text{ kg} \times 9.8\text{m/s}^2)}{(4 \times 10^{-6}\text{m}^2)(2 \times 10^{11}\text{N/m}^2)} = 7.35 \times 10^{-6}$$

Examples

A 5 m long copper wire of cross-sectional area 4 mm^2, hangs from a tall support. What would be the extension of the wire if a load of mass 2.5 kg is suspended to its free end? ($Y = 2 \times 10^{10}$ Pa)

Solution: $L_0 = 5$ m, A = 4 mm^2 = 4×10^{-6}m^2, m = 2.5 kg

The tensile force applied to stretch the wire is the same as the weight hanged on the wire,

$$F = mg = (2.5\text{ kg})(9.8\text{ m/s}^2) = 24.5\text{ N}$$

The tensile stress becomes

$$\text{Tensile stress} = \frac{F}{A} = \frac{24.5\text{N}}{4\times10^{-6}\,\text{m}^2}$$

$$\text{Tensile stress} = 6.125\text{MPa}$$

The extension of the wire can be derived from the formula of Young's modulus. Thus,

$$\Delta L = \frac{FL_0}{YA} = \frac{(\text{Tensile stress})L_0}{Y} = \frac{6.125\times10^6\,\text{Pa}\times5\text{m}}{2\times10^{10}\,\text{Pa}}$$

$$\Delta L = 1.531\text{ mm}$$

Hooke's Law

An elastic material, subject to an external force, restores its original shape or size after the removal of the deforming force, provided that the force is below the elastic limit. Hooke's law is stated as:

The amount of deformation is directly proportional to the deforming force.

Thus, Hooke's law works below the elastic limit. For example, if a force F, stretches a spring, the extension x, of the spring is directly proportional the applied force. Thus,

$$F = kx \qquad (6.4)$$

where the proportionality constant k is known as the stiffness of the spring.

The SI unit of stiffness is N/m. The constant k is the slope of the applied force vs extension graph, as shown in Figure 6.10.

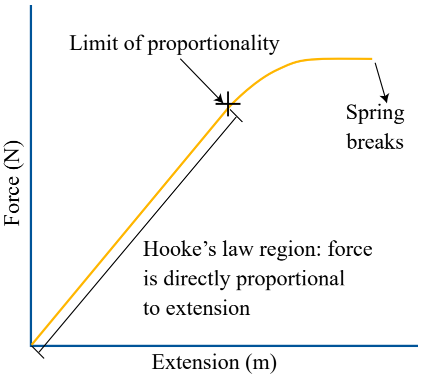


Figure 10. Graph of applied force vs extension

$$P = YS \qquad (6.5)$$

where $P = F/A$ is tensile stress and $S = \Delta L/Lo$ is tensile strain. Since Young's modulus for a substance is constant, Hooke's law can be re-stated as:

Strain S is directly proportional stress P, where Pis below the elastic limit.

This is also Hooke's law, where $\Delta L = x$. The proportionality constant k is called the stiffness of the elastic material. Its SI unit is Newton per m (N/m).

Work done on elastic strings or springs

If a string or spring obeys Hooke's Law it is called elastic. All string/springs are light. That is, they don't extend under their own weight. Elastic strings are strings which are not of a fixed length (they can be stretched). Some strings are more stretchy than others and the modulus (or modulus of elasticity) of a string is a measure of how stretchy it is.

What has been said about strings also applies to springs. However, springs can be compressed as well as stretched. If a spring is compressed, then Hooke's Law still applies. As you can see in Figure 11, whether the spring is compressed or stretched, the elastic restoring force always acts towards the equilibrium position (x = 0) of the spring.

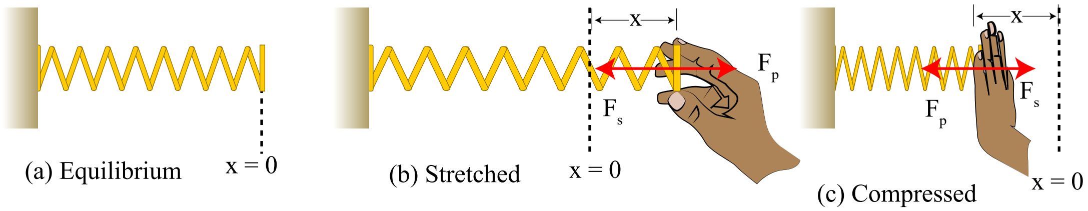


Figure 11. Spring (a) At equilibrium position (b) Stretched (c) Compressed

Suppose the spring, shown in Figure 11, has stiffness k. When a force F is applied on the free end of the spring, the spring extends proportionally with the force. To stretch the spring from zero to x, the force should increase from zero to F = kx. The average force on the spring is then,

$$F_{av} = \frac{0 + kx}{2} = \frac{1}{2}kx$$

The word done on the spring to stretch it by x is, then

$$W = F_{av}x = \left(\frac{1}{2}kx\right)x$$

$$W = \frac{1}{2}kx^2 \qquad (6.4)$$

This equation works for an elastic string of stiffness k.

Examples

How much work has to be done to stretch a spring of stiffness 250 N/m by 4 cm?

Solution:

x = 4 cm = 0.04 m, k = 250 N/m

The work on the spring is

$$W = \frac{1}{2}kx^2 = \frac{1}{2}(250\ N/m)(0.04m)^2$$

$$W = 0.2J$$

If the force is removed, the elastic restoring force exerts an equal amount of force in the opposite direction and will do the same amount of work to restore the original shape and size of the spring.

Exercises

1. What are the factors affect elasticity of a material?
2. What is elastic deformation?
3. What is plastic deformation?
4. Define tensile stress.
5. What is Elastic (Young's) Modulus?
6. Does Young's modulus of a material depend on its shape or size?
7. What does elastic modulus measure?
8. Define Hooke's law.
9. Express the stiffness of an elastic string in terms of its original length, cross-sectional area and Young's modulus?
10. Describe dectile, brittle and malleable materials.
11. A 6 m long wire has a cross-sectional area of 8 mm^2. It hangs from a tall ceiling, and a load of 8 N is attached to its end. If its tensile strain is 7.35×10^{-6}
    (a) What is the extension?
    (b) What is Young's modulus of the wire?
12. A force, applied to compress spring of stiffness 400 N/m, did a work of 0.02 J?
    (a) How far was the end of the spring displaced from its undisturbed position?
    (b) What is the maximum force applied to compress the spring?

Small drops of mercury form spherical bead instead of spreading on the surface (since you know the fact that liquids assume the shape of the container). Soil particles that were separated at the bottom of a river stick together when they are taken out instead of remaining separated. Liquids rise (or fall) in a thin capillary tube as soon as the capillary touches the surface of the liquid. The surface of a liquid will form a curved shape when a needle is placed carefully on the surface of the liquid. All these and other similar phenomena are caused due to the characteristic property of liquids, known as surface tension, which is the concern of this topic.

What is surface tension?

The intermolecular forces acting at all sides of a molecule located inside the bulk of liquid will cancel out and a molecule inside the bulk does not experience any net force. But a molecule, located on the surface of the liquid, experiences net attractive force directed towards the interior of the liquid (Figure 6.12), due to the molecules below it and as there are no molecules above it. This net force is the cause of surface tension. The SI unit of surface tension is N/m (newton per meter).

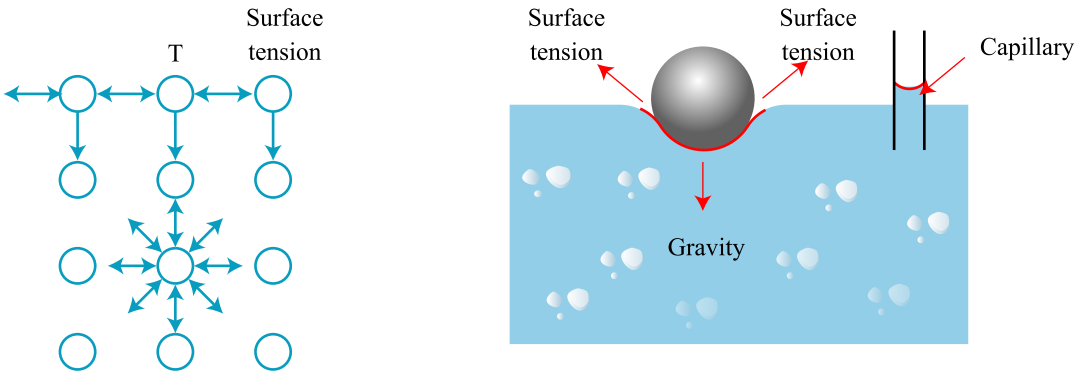


Figure 12. Showing differences on forces

Surface tension is defined as a cohesive effect of the surface of the liquid due to the forces between atoms or molecules of liquids. This phenomenon is mostly observed in the formation of soap bubbles and when a razor blade is placed on water surface with its flat part.

The magnitude of surface tension of a liquid depends on the attractive intermolecular forces between the molecules. When this force is large, the surface tension is large. Surface tension can be reduced by heating the liquid so that dispersive thermal energy is increased and the effectiveness of intermolecular attraction is decreased. Some examples of surface tension are given below.

- If water is poured using a water dropper, the water falls in a series of drops but does not flow in a continuous stream. The shape of the drops is formed by the surface tension of the water. The falling drops of water are not perfectly spherical as the force of gravity distorts them. What would be the shape of a drop of water in the absence of gravity? Why?

The drop would minimize the surface area in order to minimize tension, which would result in a perfectly spherical shape.

- Several insects, such as the water strider, are able to walk on water. They form their legs such that it distributes its weight causing a depression on the water surface. This minimizes the potential energy to create a balance of forces so that the strider can move across the surface of the water without breaking through the surface.
- Although the density of needle is greater than that of water, it is common experience to see it floating. This is because; the surface tension along the depression is enough to balance the force of gravity pulling down on the steel needle.

ACTIVITY 3

Group discussion

- Toothpaste contains soap. What is the use of the soup in the toothpaste?

Anatomy of a soap bubble

When a soap bubble is blown, a pressurized bubble of air, which is contained within a thin, elastic surface of liquid, is created. Soap is generally used in such process since most liquids cannot maintain a stable surface tension to create a bubble.

When the bubble is blown, the surface film tends to contract causing an increase in the pressure inside the bubble. A soup bubble has two liquid-gas interfaces - the one on the inside of the bubble and the other on the outside of the bubble. In between the two surfaces is a thin film of water.

ACTIVITY 4

Demonstrating surface tension

A needle, a small amount of water (without food dye), a clear glass or plastic dish or bowl, and an overhead projector are needed. To demonstrate surface tension,

- Place a small amount of water (~1 cm deep) in a shallow glass or plastic dish (or plate), and place the dish on an overhead projector.
- Turn on the projector, and carefully place a needle on the water surface so that the needle floats.

- Check whether you are able to see a projection of the needle's silhouette as it floats on the water surface or not.
- After a minute, the demonstrator will agitate the water surface with his/her finger or a pencil.
- Observe the imbalance of forces at the surface is disturbed, and the needle is sinking to the bottom of the glass dish.

Ideas for discussing the demonstrations in class

- Adhesion between water and glass leads to capillary rise in a glass tube. The cohesive force of water molecules is responsible for the phenomenon of surface tension. Therefore, tak8ing water in a glass vessel, which force is stronger; adhesive or cohesive?

Exercises

1. What force is responsible for surface tension?
2. Define surface tension?
3. Does heating reduce or increase the surface tension?
4. What would be the shape of a drop of water in the absence of gravity? Why?
5. A drop of water would minimize the surface area in order to minimize tension. So, what should be the shape of its surface in order to have the minimum surface area?
6. The density of needle is greater than that of water but it floats in water. Why?
7. Describe a soap bubble in terms of surface tension.

The molecular model of matter describes a fluid as consisting of lots of particles (atoms or molecules) moving around very fast. Collisions between the molecules make the particles of the fluid change directions and speeds often and randomly. Here you will deal with two different phenomena that depend on these random molecular interactions: viscosity and diffusion. Viscosity is the way collisions with other parts of the fluid slow down faster moving bits of fluid and diffusion is the way collisions spread out concentrations of molecules. You will also learn about materials that exhibit viscous, elastic and viscoelastic behaviors.

Diffusion in Solids, Liquids, and Gases

Diffusion is the spreading out or mixing of a substance with another substance caused by the motion of its particles. You may smell food being cooked in a kitchen while you are outside the kitchen. Because of diffusion in the air, the vapour from the food reaches you and gives you the fragrance of food. Salt, dissolved at the bottom of glass bottle, changes the taste of the whole water due to diffusion. Carbonated drinks are made by allowing gas to diffuse through water. Aquatic animals, living inside water, breathe dissolved oxygen in the water.

The process of diffusing a substance into another substance continues until a homogeneous mixture is achieved. Diffusion is a phenomenon that occurs in gases, liquids, and solids, that is determined by the movement of its particles. In gases, diffusion is the fastest, whereas in solids, it is the slowest. Diffusion in liquids is slower than that in gases and faster than that in solids. Various gases have different diffusion rates depending on their density. Denser gases mix together at a slower rate than lighter gases. Density and temperature are the major factors that affect diffusion.

- The higher the density of the diffusing substance, the lower the rate of diffusion.

As the temperature rises, the constituting particles of the diffusing substance travel faster, resulting in an enhanced rate of diffusion. For example, one can smell cold food from a short distance, whereas can smell hot food from a long distance.

Viscosity in solids, liquids and gases

Viscosity is one of the characteristic properties of fluids, which is a measure of resistance to flow. It arises due to the internal friction between layers of fluid as they slip past one another while the fluid flows.

A. Viscosity in liquids

In liquids, viscosity is due to the strong intermolecular forces between molecules. When a liquid flows over a fixed surface, the layer of molecules in the immediate contact of surface is stationary. As we go up from the stationary surface, the velocity of upper layers increases. This type of flow in which there is a regular gradation of velocity in passing from one layer to the next is known as laminar flow. For a given arbitrarily chosen layer in the flowing liquid, the layer above it accelerates its flow whereas the layer below this retards the flow, as shown in Figure 6.13.

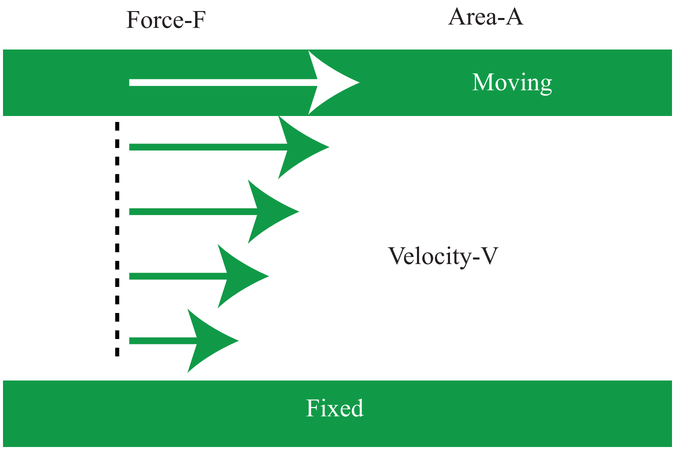


Figure 13. Laminar flow of water

The greater the viscosity, the more slowly the liquid flows. Hydrogen bonding and van der Waals forces are strong enough to cause high viscosity. Glass is an extremely viscous liquid. The reason why many of the properties of glass resemble that of solid is that it is a very viscous liquid. If you measure the thickness of the windowpane of an old building, you will find that the glass is thicker at the bottom and thinner at the top.

Viscosity increases with an increase in pressure (except water). Viscosity increases with an increase in the density of the liquid. Since honey is denser than water, it is more viscous.

Figure 14. Honey is more viscous than water.

Since force due to thermal energy acts against intermolecular forces, viscosity of liquids decreases as the temperature rises. That is, at high temperature molecules have high kinetic energy and can overcome the intermolecular forces to slip past one another between the layers. On the other hand, viscosity increases with pressure.

For most lubricants this effect is considerably larger than the other effects when the pressure is significantly above atmospheric pressure.

B. Viscosity in gases

Measurement of viscosity in fluids requires laminar flow. Flow of gas in capillary tube is assumed to be laminar flow. Thus, to measure viscosity of gas, a sample of an ideal gas is drawn through a thin capillary tube. As is seen in the case of liquids, the layer along the wall of the capillary has a velocity of zero. The fluid flows more quickly the further away it is from the stationary wall.

Unlike liquids, the intermolecular force between molecules of gases is very weak. The viscosity on a gas arises due to friction only. Adjacent laminar sheets experience friction as they slide past one another. In gases, molecular collisions transfer momentum between fluid layers. As slower molecules collide with faster molecules, the slower molecules speed up and the faster molecules slow down. As temperature increases, the molecules move faster and more momentum is transferred between layers, thereby increasing the viscosity.

Viscosity decreases with an increase in density. Viscosity decreases with an increase in pressure.

C. Viscosity in solids

Since solids do not flow, you can shear solid by a shear stress. Suppose you are spreading butter on toast by applying a shear stress. You will observe that heated butter will move at a faster rate for the same applied stress as compared to unheated butter.

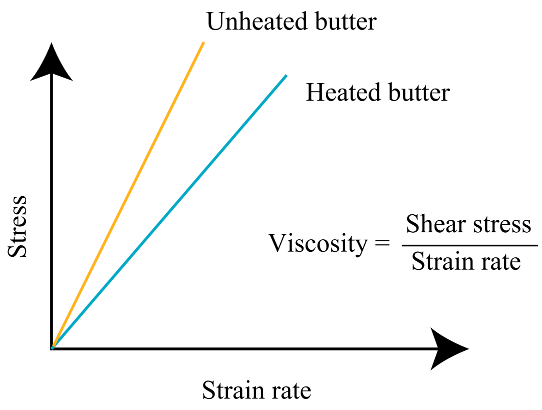


Figure 15 Impact of temperature on viscosity

The other key difference between solids and liquids is that in liquids, molecules have the possibility to move at a certain speed relative to neighboring molecules in contact. However, neighboring atoms in solids are fastened together but can be stretched or compressed. You can treat it as if its atoms were connected by springs. Anytime you move a single atom, you stretch a spring, and need a force to do so. But liquids are different in that there's no significant force required to displace individual molecules, instead you require a force to move molecules relative to other molecules at a certain speed (strain rate). Viscosity is the slope of the stress vs strain rate graph, see Figure 15. Strain rate is change in strain per unit time.

Strain rate of elastic string vs viscous materials

Viscous materials, like water, resist shear flow and strain linearly with time when a stress is applied. Elastic strings strain when stretched and immediately return to their original state once the stress is removed.

Elasticity is usually the result of bond stretching along crystallographic planes in an ordered solid, where as viscosity is the result of the diffusion of atoms or molecules inside an amorphous material.

The graphs in Figure 16, compares strains on ideal viscous liquids, and ideal elstic solids when a constant stress is applied on them for given time t.

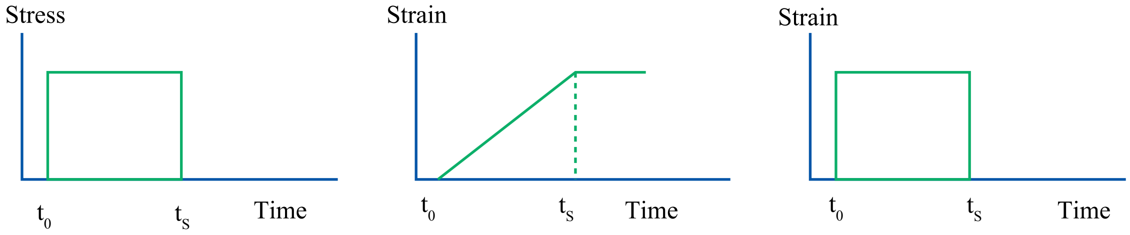


Figure 16. compares strains on ideal viscous liquids, and ideal elstic srigs when a constant stress is applied on them.

Exercises

1. What is diffusion?
2. When does the diffusion of one substance into another cease?
3. Does the rate of diffusion increase or decrease as the pressure rises? why?
4. Among the three states of matter, in which one is diffusion, the fasters?
5. Do all gases have the same diffusion rate?

6. Does the rate of diffusion increase or decrease as the temperature of the diffusing substance rises?
7. What is viscosity? How does viscosity arise?
8. Can viscosity be a result of strong intermolecular forces between molecules?
9. What is laminar flow of a fluid?
10. In which state of matter is viscosity the highest?
11. What is viscoelasticity property of materials?
12. How does viscoelasticity differ from elasticity?
13. Which type of substance shows dependent strain elastic or, viscoelastic?

Summary

- Anything in the universe that has mass and volume is made up of matter. Matter can exist in different forms due to the internal and external factors.
- At a given temperature and pressure a substance can exist mainly in one of three major states of matter: solid state, liquid state, and gaseous state of matter.
- All matter is composed of atoms, each of which has a central nucleus and one or more electrons moving around the nucleus.
- There are two major types of chemical bonds: covalent bonds and ionic bonds.
- A molecule is the simplest unit of a covalent compound that contains the physical and the chemical properties of the compound.
- One important application of kinetic theory is that it helps to explain why matter exists in the three different phases and how matter can change from one state to the next.
- Intermolecular forces are forces between interacting molecules and can be either attractive or repulsive. This force is attractive between neighboring molecules until they are very close and electrostatic forces come into play.
- The magnitude of the repulsion rises very rapidly as the distance separating the molecules decreases. This is the reason that liquids and solids are hard to compress.
- Attractive intermolecular forces are known as van der Waals forces. The van der Waals forces or van der Waals bonds in water are due to unsymmetrical

charge distribution in the molecule that leads to a net attraction between polar molecules.

- Thermal energy is the energy of a body arising from motion of its atoms or molecules. It is directly proportional to the temperature of the substance. This movement of particles is called thermal motion.
- Thermal motion in a substance produces a dispersive force. This force acts opposite to the attractive intermolecular force.
- The attractive intermolecular forces tend to keep the molecules together by canceling out the dispersive force due to their thermal energy.
- The attractive forces between like molecules or atoms are referred to as cohesive forces. Attractive intermolecular forces between unlike atoms or molecules are said to be adhesive forces.
- Elasticity is the property of matter by virtue of which the deformed body returns to its initial configuration after the removal of the deforming force.
- The maximum force that the object can withstand without being permanently deformed is called the elastic limit.
- Plastic deformations are deformations where irreversible changes occur on shape or size after it is being deformed.
- The relative displacements of the various parts of a body under the action of an external force produce an internal force tending to restore the body to its original configuration.
- According to Newton's third law, the internal force is equal in magnitude but opposite in direction to the applied force. Stress is measured at equilibrium.
- Tensile deformation occurs when two forces of equal in magnitude and opposite in direction act perpendicularly on the cross-sections of opposite ends of a material such as a rod or a wire.
- Tensile stress is defined as the ratio of tensile force F to the cross – sectional area A of the wire.

$$\text{Tensile stress} = \frac{F}{A}$$

- Tensile strain is defined as the fractional change in length; i.e., the ratio of the extension L produced by the tensile stress to the original length (L0) of the wire.

$$\text{Tensile strain} = \frac{\text{Extension on the wire}}{\text{Original length}} = \frac{\Delta L}{L_0}$$

- The stress applied to a wire produces a strain in it. Young's modulus measures how much the wire stretches. It is defined as

$$\text{Young's Modulus} = \frac{\text{Tensile stress}}{\text{Tensile strain}}$$

$$Y = \frac{FL_0}{A\Delta L}$$

The SI unit of Young's modulus is N/m^2.

- Hooke's law is stated as the stretch on a body is directly proportional to the applied force, provided that the applied force is below the elastic limit of the material.

$$F = kx$$

where the proportionality constant k is known as the stiffness of the material and its SI unit is N/m.

- Surface tension is caused by the forces of attraction between the particles of the liquid and the other substances with which it comes in to contact.
- Surface tension is defined as a cohesive effect of the surface of the liquid due to the forces between the liquids atoms or molecules.
- The magnitude of surface tension of a liquid is large when the attractive intermolecular forces between the molecules are large. Hence surface tension can be reduced by heating the liquid
- Diffusion is the spreading out or mixing of a substance with another substance caused by the motion of its particles.
- The process of diffusing a substance into another substance continues until a homogeneous mixture is achieved.
- The higher the density of the diffusing substance, the lower the rate of diffusion.
- As the temperature rises, diffusion rate increases.
- Viscosity arises due to the internal friction between layers of fluid as they slip past one another while fluid flows.
- In liquids, this resistance is due to the strong intermolecular forces between molecules.

- The greater the viscosity, the more slowly the liquid flows. Hydrogen bonding and van der Waals forces are strong enough to cause high viscosity.
- Increase in temperature reduces viscosity.
- Viscoelasticity is the property of materials that exhibit both viscous and elastic characteristics when undergoing deformation.

Exercises

1. Which theory describes the arrangement and movement of particles in solids, liquids and gases?
2. In which state of matter are the particles mostly touching but arranged in a random way?
3. In which state of matter do the particles have the most energy?
4. Why can liquids not be compressed easily?
5. Why do solids have a fixed shape?
6. What eventually happens if energy is continually removed from a liquid?
7. What eventually happens to a gas if its pressure is increased?
8. What are the forces of attraction and repulsion between interacting molecules?
9. Hydrogen bond plays a vital role in determining substance properties and structure. Write an example/
10. Do molecules exert repulsive forces on one other?
11. What are the differences between the two major types of chemical bonds?
12. What are the factors that affect the elastic limit of deformation?
13. A wire 15 m long has a cross-sectional area 1.2×10^{-4} m^2. It is subjected to a load of 6 kg. If the elongation is 10^{-4} m, determine the Young's modulus of the material?
14. One end of a 10 m long wire and diameter of 10^{-2} m, is fastened on a ceiling. What would be the extension if a load of 5 kg is suspended on the other end? Take the Young's modulus of the material be 3.8×10^{10} N m^{-2},
15. A spring of stiffness 1000 N/m is compressed from its equilibrium position to 5 cm.
    (a) What is the average force exerted on the spring?
    (b) How much work is done in compressing the spring?
16. What is the main cause of surface tension?
17. What are the factors that affect the magnitude of surface tension?

18. When does the process of diffusing a substance into another substance stop?
19. What are the effects of heating on viscosity and diffusion?
20. What are the effects of pressure on viscosity and diffusion?
21. While writing something on a blackboard and then leaving it filthy for an extended length of time, cleaning the blackboard becomes pretty tough. Does this phenomenon have something with diffusion?
22. Does diffusion have something to do on the formation of alloys?
23. Does diffusion have something to do on the mixing of oxygen from our lungs into the blood streams?

WHAT IS BULLYING?

Any unwanted written, verbal, graphic, or physical act by an individual or group toward another person(s) that causes harm or distress.

Types of Bullying

- Physical
- Verbal
- Social
- Emotional
- Cyber

Signs of Bullying

- Headaches
- Depression
- Loss of friends
- School absenteeism
- Academic problems

What You Can Do

PREVENT

- Be a role model for positive communication, healthy relationships, and self-care.
- Reinforce acts of kindness, respect, and inclusion.
- Set policies and rules about bullying.

RECOGNIZE

- Know the definition of bullying and its many forms.
- Talk with and actively listen to the youth who confide in you.
- Watch for warning signs of bullying.

INTERVENE

- If you witness bullying behavior
- Respond quickly and consistently to send the message that it is not acceptable.
- Separate the students involved.
- Meet any immediate medical or mental health needs.
- Stay calm and model respectful behavior.

Source: Teacher's Diary on *Cyber-Crime Awareness* by UNODC, Cybercrime and MoE, Republic of Liberia

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Teacher : ______________________ Subject: ____________________

Grade : ____

No.	Name of the Student	Name of the Textbook	Barcode Number	Condition of the TB when received	Date Received	Date Returned	Condition of TB when returned	Signature of Student
1								
2								
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